Magnetic Reconnection in the Earth's Magnetosphere

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Abstract

The process of magnetic reconnection plays an important role during the interaction of the solar wind with the Earth's magnetosphere which leads to the exchange of mass, momentum, and energy between these two highly conducting plasmas. Evidence for magnetic reconnection occurring at the magnetopause vis a vis the expected signature from the reconnection model will be discussed. Magnetic reconnection is also believed to play an important part in magnetospheric substorms, which occur in the magnetotail and are characterized by explosive releases of energy. Relevance of spontaneous as well as driven reconnection to rnagnetospheric substorms will be highlighted.

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1 GENERAL BACKGROUND

The interacion of a highly-conducting solar wind with the geomagnetic field leads to the formation of the magnetosphere. The geomagnetic field acts as an obstacle and deflects the solar wind (which is an ionized and highly conducting gas, consisting mainly of electrons and protons (with $\sim 3\%$ He^{++}), being emitted continuously from the Sun) flow resulting in the formation of a cavity which is known as the *magnetosphere*. The boundary of the magnetosphere is called the magnetopause (see Figure 1). As a result of the solar wind-geomagnetic field interaction, the geomagnetic field is compressed on the dayside (to $\sim 10\ R_E$) and stretched on the night side into a long tail extending beyond 1000 R_E, where R_E is the Earth's radius. Further, the magnetosphere extracts energy from the solar wind continuously at low levels and sporadically at high levels, and dissipates it by setting up a complex pattern of several current, systems, as shown in Figure 1. The flow of the solar wind across the open geomagnetic field lines constitutes the solar wind-magnetosphere (SM) dynamo. 'l'he SM dynamo is the major generator of electric fields and currents in the magnetosphere [*Lakhina*, 1993a].

The magnetopause represents the outer boundary of the magnetosphere which separates the colder and denser plasma in the magnetosheath from the hot tenuous plasma in the magnetosphere. The magnetic fields on either side of the magnetopause are generally of different magnitudes and directions. The physical processes occurring at the magnet opause control the exchange of energy, momentum and mass from the solar wind to the magnetosphere, and thus drive such phenomena as large-scale convective motions, substorms, and auroras.

In the early closed model of the magnetosphere based on the frozen--f eld concept (see Fig. 2a), the magnetopause was treated as a tangential discontinuity as no interaction between the geomagnetic field and the interplanetary magnetic field (IMF) embedded in the solar wind was allowed. The open magnetosphere model is based on the concept of magnetic reconnection which was introduced into magnetospheric physics by *Dungey* [1961] (see Fig. 2b). This model treats the magnetopause as a boundary layer which allows the entry of the solar wind plasma and fields into the magnetosphere. Hence, in the open magnetosphere model, the magnetopause is treated essentially as a rotational discontinuity. Further, magnetic reconnection at the magnetopause sets up large-scale convection in the magnetosphere, and the accumulation of magnetic flux into the magnetotail. This stored magnetic energy is believed to be converted into plasma energy, and subsequently released explosively during magnetospheric substorms.

In secion 2, we shall consider the magnetic reconnection at the magnetopause. Section 3 will deal with the magnetospheric substorms and the reconnection model. The processes of driven reconnection and disruption] of forced thin current sheets will be discussed briefly.

2 Magnetic Reconnection at the Magnetopause

Magnetic field line reconnection is a process whereby plasma flows across a surface that separates regions containing topologically different magnetic field lines. The magnitude of plasma flow is a measure of the reconnection rate [*Vasyliunas*, *1975]*. Reconnection occurs when an electric field is present along a magnetic separator (i.e., X-line or the reconnection line) in a plasma. During this process, the magnetic energy is converted into plasma kinetic energy, and the system relaxes to a lower potential energy state with a different magnetic topology.

2. I Steady-state reconnection model

The first quantitative analysis of the magnetopause reconnection was done by *Levy et al. [1* 964]. They considered a steady-state two-dimensional MHD model for the magnetopause, as shown in Figure 3. Futher, they considered a situation with a cool, dense plasma on one (magnetosheat h) side, and a hot, tenuous plasma on the other (magnetosphere) side. This configuration is referred to as the *asymmetric* case, as opposed to the *symmetric* case considered by *Petschek* [1964], where the plasma conditions on both sides of the current sheet are taken to be identical. This latter model has been refined and put on a more realistic quantitative footing for application to magnetopause data by *Yang and Sonnerup* [1976], *Heyn et at.*[1988] and *Biernet et al.* [1990].

In Figure 3, the magnetopause appears as a rotational discontinuity having a finite normal magnet ic field component, B,,, which connects the magnetosheath field lines with the magnetospheric field lines. A rotational discontinuity, in an MHD fluid with isotropic pressure, is characterized by the normal flow velocity equal to the Alfvén velocity based on the normal magnetic field component, B_n. The reconnection site is the line (i.e., the separatrix, or X-line) in the equatorial plane (i.e., the plane perpendicular to the plane of Figure 3) where two magnetic field surfaces, the separatrices $S1$ and $S2$, intersect each other and create a null in tile field.

In Figure 3, the magnetosheath plasma is moving to the right towards the [magnetosphere. Most of it flows around the magnetosphere, which forms an obstacle to tile flow, but a fraction crosses the magnetopause as a result of the presence of the B_n field. This component is negative, that is $B_n < 0$ when it is directed towards the Earth, north of the separator, and positive ($B_n > 0$, pointing away from the Earth) south of it. The plasma flow is not field-aligned but takes place along streamlines, shown as dashed lines, which cross the magnetic field. Such cross-field flow requires the presence of an electric field, $\mathbf{E}_t$, tangential to the magnetopause, and along the separator where reconnection occurs.

From Figure 3, it is noted that the reconnection electric field, $\mathbf{E}_t$, is parallel to the magnetopause current, I, commonly known as Chapman-Ferraro current. Since $\mathbf{E}_t \cdot \mathrm{I} > 0$, this situation implies the conversion of electromagnetic energy into plasma energy. In this MHD model, the energy is carried away by the high-speed plasma jets emanating from the reconnection site in two-wedge shaped regions attached to the inside of the magnetopause and with vertices at the separator. They comprise the plasma boundary layer (BL) (see Fig. 3). We must emphasise that only a small fraction of these jets, namely the layer closest to the Earth, contains rnagnetosheath plasma that has passed through the *diffusion region* where the magnetic reconnection takes place. Most parts of these jets are populated by plasma that has crossed the magnetopause away from the diffusion region, and at the same time, has suffered acceleration, away from the reconnection site and tangential to the magnetopause, by the I x $\mathbf{B}_n$ force. These plasma jets are the principal features of the reconnection process. However, the jets should be very narrow and it is difficult to observe them without high time resolution plasma and field data. In fact the controversy about the magnetopause reconnection being reality arose because of the absence of direct observation of such high-speed jets [*Heikkila*, 1975; *Haerendel et al.*, 1978].

On the other hand, if reconnection were not taking place, the magnetopause should be a tangential discontinuity with B_n = O. A tangential discontinuity describes a boundary across which there is no mass flow and which does not support a normal component of the magnetic field. Therefore. at the tangential discontinuity, the velocity and the magnetic field are both tangential and they can have any value in both direction and magnitude. For the case of magnetopause behaving as a tangential discontinuity, E_t in side the magnetopause should more or less vanish, and the magnetosheath plasma could cross the magnetopause layer only by a diffusive transport process (the so called *viscous* interaction).

2.2 Signature of reconnection

From the above discussion it is clear that the direct proof of the occurrence of steady state reconnection at the magnetopause (or anywhere else as a matter of fact!) are:

1. Presence of a tangential electric field, $\mathbf{E}_t$, along the separator (as this being the standard definition of reconnection), consistent with the motion of plasma towards and across the magnetopause, and its direction must be such that $\mathbf{E}_t \cdot$ I > 0 such that the electromagnetic energy could be converted into kinetic energy of plasma.

2. Presence of normal component, B_n, of the magnetic field which is directed inward north of the X-line and outward south of it.

3. There is a normal component of flow velocity (i.e., inward directed plasma flow) given by

$$(v_n - U_n) = \frac{B_n}{\sqrt{\rho\mu_0}}, \tag{1}$$

   where ρ is the mass density and v and U are the plasma flow velocity and the magnetopause velocity measured on the spacecraft, respectively. The subscript "n" denotes the normal component.

4. Plasma which has crossed the magnetopause (i.e., plasma in the downstream region) must exhibit a change in the tangential flow velocity given by

$$[v_t] = \left[\frac{B_t}{\sqrt{\rho\mu_0}}\right], \tag{2}$$

   where the suscript '(t" denotes the component tangential to the boundary, and the square bracket $[f]$ denote the difference between the values of any physical quantity, f, on two side of the boundary layer.

Equations (1) and (2) follow directly from the continuity of $\mathbf{E}_t$, conservation of the mass flux, and the continuity of momentum flux across the magnetopause boundary (here treated as a rotational discontinuity) [*Hudson*, 1971].

2.3 Observational evidence

2.3.1 Tangential electric field

Reliable measurements of the tangential electric field, $\mathbf{E}_t$, in the plasma environment of the magnetopause are difficult. Further, it is not easy to identify the narrow diffusion region around the separator, as we do not know what plasma processes to look for. The motion of the magnet opause boundary creates further difficulties in transforming the observed small electric fields into a reference frame fixed with respect to the magnetopause.

Moreover, it is very unlikely that a satellite crossing the magnetopause will encounter the diffusion region. Rather it will pass through the current layer away from the diffusion region. It is still possible to obtain persuasive evidence for reconnection under this situation. 'l'his is so because an electric field $\mathbf{E}_t$ tangential to the magnetopause or a magnetic field component B_n normal to it, if present over a region of scale lengths much larger than the magnetopause thickness, would indicate that reconnection is occurring or has occurred in the recent past. According to this reconnection model, the magnetopause will act as the rotational discontinuity leading to an "open" magnetosphere.

Mozer et al. [1979] were the first to observed a persistent positive $\mathbf{E}_t$, having amplitude of a few mV/m, at the magnetopause, their results are shown in Figure 4. From their measurements, and on neglecting the induction electric fields, they were able to deduce energy dissipation of $\mathbf{E}_t$. I ~ 70 W km^{-2}. Later on *Sonnerup et al.* [1981] reported magnetopause tangential electric fields having amplitudes of 0.8 – 2.8 mV/m from 11 magnetopause crossings.

2.3.2 Normal magnetic field

pleasuring normal component B_n of the magnetic field accurately at the magnetopause is a formidable task, since, for reasonable reconnection rates, B_n is expected to be only a few nanoTesla. This means that the local magnetopause normal must be known to within an accuracy of a few degrees. As the magnetopause is rarely stationary, ant{ its surface keep on changing shapes due to excitation of surface waves or other kinds of ultralow-frequency waves due to the presence of velocity shears and gradients in plasma and fields [*Lanzerotti and Southwood*, 1979; *Lakhina et al.*, 1993], a model normal is not useful for this purpose. *Sonnerup and Cahill* [1967] developed a method based on *minimum variance technique* for determining B_n from the magnetopause magnetic field measurements. In a one-dimensional magnetopause, B_n is strictly constant as demanded by $\nabla \cdot \mathbf{B} = 0$. Since in practice it is difficult to find such a direction along which B_n is strictly constant, this method chooses as an approximation the direction which yields minimum variance in the corresponding field component.

Occasionally, reliable normal vectors ant] B_n values are obtained by the method of *Sonnerup and Cahill* [1967]. Figure 5 shows an example where the minimum variance technique is able to determine a finite B_n with high confidence level [*Sonnerup and Ledley*, 1979]. In this figure, data for a 3-second interval during magnetopause crossing are shown as hodograms, in the coordinates obtained from minimum variance analysis of the observed magnetic field. Here, B_3 corresponds to that of minimum variance and, therefore, it is identified with B_n. On the other hand, B_1 and B_2 corresponds respectively to the axis of maximum variance, and to that of intermediate variance. The hodogram on the left, drawn in the plane tangential to the magnetopause, shows the semi-circular shape characteristic of a rotational discontinuity. The hodogram on the right of Figure 5 clearly shows the normal component $B_n \sim (8.0 \pm 0.4)$ nT.

2.3.3 normal plasma flow velocity

The normal component of the flow velocity, v_n, like $\mathbf{E}_t$ and B_n, is also proportional to the reconnection rate and is equally, if not more so, difficult to measure. It is found that B_n values obtained from the minimum variance method and v_n values obtained from the projection of measured plasma flow vectors along n often have large uncertainties due mainly because of magnetopause boundary motions and undulations of its surface. Therefore, test 3 can rarely be applied on an individual magnetopause crossing. *Sonnerup et al.* [1981] performed this test with values of B_n and v_n obtained from averaging over 11 magnetopause crossing and found agreement with (1).

2.3.4 Tangential flows

The tangential flows are not sensitive to the choice of magnetopause normal, and are expected to be quite large. However, these flows can assume arbitrary directions and occur in narrow wedge shaped regions. Therefore, three-dimensional flow measurements with high time resolution are required to analyse the tangential flows. We shall discuss the observational test of the relationship between the tangential plasma flow and the magnetic field component as given by ('2) [*Paschmann et al.*, 1979; *Nishida*, 1979; *Sonnerup et al.*, 1981 ; *Haerendel (111(1 Paschmann*, 1982].

Figure 6 shows the polar plots of the magnetic field, B, and plasma flow velocity, v, for an outbound crossing of the subsolar magnetopause at a latitude of $\sim 25°$, in the coordinate system obtained from the minimum variance analysis. From the tangential hodogram (on the left side) we note that the changes in the magnetic field and velocity across the magnetopause arc nearly parallel as demanded by (2). On taking the change in $\mathbf{B}_t$ between points 1 and 2 in the tangential hodograms, and the measured plasma mass density, and using these values in (2), the predicted change in plasma velocity is about 580 km s^{-1}. The actually measured change in the tangetial velocity from Figure 6 is about 425 km S-*. In view of the difficulty in making accurate three-dimensional flow velocity measurements, this can be taken as a fairly good agreement. The conclusion that the magnetopause can have a structure of a rotational discontinuity as required by reconnection has been confirmed by *Sonnerup et al.* [1981] from a detailed analysis of 11 such cases as shown in Figure 7.

2.3.5 Indirect evidence

In this section, we shall cite some observations which provide indirect support for the existence of reconnection at the rnagnetopause.

1. open magnetosphere: Observations concerning direct access of energetic solar electrons, emitted during solar active periods, to the Earth's polar caps provide strong support for an open magnetosphere. The intensity profile of the 376 keV electrons measured by polar orbiting satellites is found to be flat near the central polar cap, indicating a uniform electron bombardment [*Vampola*, 1971]. This situation can arise only if all polar cap field lines were open, i.e., extending into interplanetary space. By contrast, in a closed magnetosphere, solar electrons could gain access to the polar cap field lines only by cross-field diffusion. This would lead to an intensity profile with a depleted central polar cap [*Morfill and Scholer*, 1973].

It is conceivable that the field lines connected with the interplanetary field lines would allow the energetic particles to escape from the magnetosphere in much the same way as they allow the energetic particles to enter the magnetosphere. 'l'here are observations which indicate the presence of layers of energetic electrons and ions outside the magnetopause but inside the outer separatrix surface [*Williams and Frank*, 1980; *Scholer et al.*, 1981]. These ate magnetospheric and ionospheric ions that have leaked across the magnetopause boundary and have been accelerated by the I x $\mathbf{B}_n$ force, as well as magnetosheath ions that have been reflected at the magnetopause.

2. *IMF correlations:* The north-south component of interplanetary magnetic field (IMF), B_z, is found to be very well correlated with the auroral electrojet (AE) index, which is a measure of the auroral electrojet intensity [*Arnoldy*, 1971; *Tsurutani and Meng*, 1972]. Similarly, the magnetic activity index, D_{st}, which is computed from mid-latitude magnetic records and is an indicator of the worldwide deviation of the magnetic H-component from its quiet time values, and the ϵ function [*Perreault and Akasofu*, 1978], which describes the energy coupling from the solar wind to the magnetosphere, are well correlated with interplanetary parameters like solar wind pressure, solar wind speed, dawn -to-dusk component of the solar wind electric field, etc. These observations show that magnetosphere is open and, thus, provide indirection evidence for the reconnection at the magnetopause.

To sum up, there is enough evidence, both direct and indirect, which strongly support the concept of collisionless steady-state reconnection occurring at the magnetopause. However, during a significant number of magnetopause crossings, no signatures for steady-state reconnection are found although the IMF had a southward component [*Haerendel et al.*, 1978; *Sonnerup and Ledley*, 1979; *Sonnerup et al.*, 1981; *Sonnerup*, 1984]. , It appears that steady-state reconnection occurs rather rarely at the magnetopause. On the other hand there is ample evidence that suggests that the reconnection at the magnetopause occurs in a nonsteady or patchy manner involving small-scale, transient erosion of magnetic flux. This phenomenon is called *flux transfer events* or simply FTEs.

2.4 Flux transfer events

Measurements from ISEE 1 and 2, and other spacecraft have shown that magnetopause reconnection is seldom a steady-state process. Rather, the magnetopause is often subjected to patchy reconnection producing a feature called the flux transfer event. FTEs are tubes of twisted magnetic field lines about 1 R_E across, connecting the magnetosphere to the magnetosheath.

Haerendel et al. [1978] observed short duration increases, or spikes, in the magnetospheric field strength in the plasma and field data collected by Heos 2 in the high latitude bounary layer. They attributed these spikes to temporally and spatially limited reconnection in the polar cusp. Similar spiky events in the rnagnetosheath were observed by *Russell and Elphic* [1978] in the ISEE data. Since the magnetic flux was being transported and the phenomenon had a beginning and an end, these events were termed “flux transfer” events.

Figure S shows first of these events that were found by *Russell and Elphic* [1978] during as inbound traversal of the magnetosheath into tile magnetosphere at low latitudes near local noon.

The data are shown in the L, M, N boundary coordinates, where coordinate N is along the local magnetopause normal, L is in tile plane defined by N and the z-axis of the solar magnetospheric (GSM) system, and M completes the right-handed system. FTEs intervals are marked by the vertical clashed lines. In the center of each event arc energetic electrons, as well as protons streaming out of the magnetosphere. Yet at the same time at low energies, the plasma is clearly the flowing magnetosheath plasma. The normal component of the magnetic field, B_N, first increases outwards and then turns inwards. The azimuthal component, or B_M, shows an increase, and the vertical component, or B_L, has a typical signature of a magnetopause crossing. The presence of energetic magnetospheric electrons and ions in these flux tubes indicate their connection to the magnetosphere and the streaming of the ions indicate that one end of the flux tube is open to the magnetosheath. The simplest explanation for these events is that reconnection takes place in a limited region for a short period of time, and the resulting tube of reconnected flux is carried away by the magnetosheath flow as shown in Figure 9. The draping of the surrounding magnetosheath field lines over the flux tube then produces the observed B_N variations, Further, the tension in the field lines tends to straighten the bend in the tube and, thus, accelerate the plasma flow in this region. From the duration of FTEs together with the plasma flow velocity, dimensions of FTEs along the boundary are found to be of the order of several R_E. Similarly, the size of the variation of the B_N component suggests that the FTE scale size normal to the boundary is of the order of an R_E.

There arc several models for the formation of FTEs at the dayside magnetopause based on magnetic reconnection [*Russell and Elphic*, 1978; *Lee and Fu*, 1985; Scholer, 1988; *Southwood et al.*, 1988; *Schindler and Otto*, 1990; *Lee et al*, 1993]. However, it has been suggested that a wavelike motion of the magnetopause caused by the solar wind pressure variations might provide an alternate explanation for the FTE signature [*Sibeck*, 1990, 1992; *Sibeck and Smith*, 1992]. Recently, *Otto et al.* [1995] have studied the magnetic field and plasma properties associated with pressure pulses and magnetic reconnection at the magnetopause using two-dimensional MHD simulations. They find that magnetic reconnection and pressure perturbations could be closely linked, so much so that pressure perturbations can actually trigger magnetic reconnection.

3 Magnetic Reconnection in the Magnetotail

3.1 Introduction

The Earth's magnetosphere has a long magnetotail with antiparallel magnetic fields in the two halves (lobes) of the tail, with a dwan-to-dusk cross-tail current flowing in the central plasmasheet located between the two lobes. The plasmasheet has been considered as a likely site for the occurrence of magnetic reconnection because of its characteristic anti-parallel field configuration. In fact, according to the open magnetosphere model proposed by *Dungey* [1961], southward IMFs reconnect to northward magnetospheric fields through the formation of an X-line at the dayside magnetopause. The open magnetic field lines formed are thus dragged by the solar wind in the anti-sunward direction, and convected into the magnetotail. Another magnetic X-1ine is formed in the magnetotail at distances $\sim$ 100 R_E (the exact location is still being debated), where the magnetic field lines from the northern and southern polar caps reconnect (see Figure '2). At this distant -Y-line or neutral line, the totally disconnected (from the Earth) field lines go back to the solar wind, but the closed field lines convect back towards the Earth and are returned to the dayside magnetopause. This large scale flow of the magnetospheric field lines or plasma, since the magnetic field is frozen into the plasma, is known as magnetospheric convection. On the average, the rate of dayside reconnection equals that of nightside, and some kind of equilibrium is maintained. However, the situation changes dramatically when the IMF is strongly southwards, and remains so for a long time. In such a case, the rate of addition of the dayside magnetic flux to the nightside keeps on increasing continuously. The magnetotail cannot store this energy indefinitely, and magnetic energy is released explosively in the form of plasma energy, supposedly via reconnection at the near-Earth neutral line, during magnetospheric substorms. Slow shocks and magnetic reconnection [*Ho et al.*, 1994; *Ho and Tsurutani*, 1995] are observed in the far tail at distances of X= -200 to -240 R_E. This has a weak dependence on substorms and is not thought to play an important role in substorm dynamics. This may be "magnetic sloughing" during quite time intervals. We shall discuss some characteristics of magnetospheric substorms, and two popular models for the substorms, and review the current status of the substorm research.

3.2 Magnetospheric Substorms

The geospace environment is dominated by disturbances produced directly by the Sun, like solar flares and coronal mass ejections which are responsible for some large geomagnetic storms [G'oJlua-

lez et al., 1994] or else by disturbances, e.g. substorms, occurring within the magnetosphere that are ultimately caused by the solar wind magnetic field variations (interplanetary Alfvén waves). A large portion of the energy extracted from the solar wind by the S-M dynamo is stored in the form of excess magnetic flux in the magnetotail region, which subsequently is explosively released in the form of energetic particles and strong plasma flows and dissipated in the near-Earth night-side region; this phenomenon is called a magnetospheric substorm. During substorm activity, the cross-tail current is disrupted and diverted towards the ionosphere as a field-aligned current, energetic particle precipitation causes enhanced auroral activity, and there is an enhancement in the westward electrojet current (AE index). Further, magnetospheric convection increases, the plasma sheet tends to move earthward and a part of the plasmasheet is severed from the earth, forming a "plasmoid" that flows tailwards. Magnetospheric substorms last from about one to a few hours. When the interplanetary convection electric field are very intense (>5 mV/m) and of long duration (> 3 hrs) geomagnetic storms which are characterized by a buildup of a ring current which manifests itself as a main phase, during which the magnetic field at the Earth's surface is greatly depressed [*Tsurutani and Gonzalez, 1997]*. During geomagnetic storms there are many intense substorms leading to the enhancement of the ring current. Although substorms always occur during geomagnetic storms, the exact relationship between storms and substorms is still being debated [*Gonzalez et* al., 1994; *Kamide et al., 1997]*. Magnetospheric substorms and major geomagnetic storms can produce intense, highly disruptive surges in energetic particle populations in the magnetosphere and rapidly-varying ionospheric- magnetospheric currents that can either completely paralyze or adversely affect the functioning of modern satellite and large power distribution grids on the ground. Thus, the magnetospheric substorms represent a global interaction between the solar wind, the magnetosphere and the ionosphere [*Kan et al.*, 1991, *Kamide and Kroehl*, 1994].

3.2.1 **Substorm** Phases

Substorms are the fundamental element in understanding the nature of geomagnetic activity. Three substorms phases, namely, growth, expansion, and recovery have been identified. The magnetosphere attains a kind of ground state (i. e., a quiet period) after a prolonged period of northward interplanetary magnetic field (IMF) in the solar wind. The growth phase usually begins with the start of southward turning of IMF. In the ionosphere, the polar cap size increases as the polar elect rojets intensify. In the magnetosphere, the cross-section of the magnet otail increases, the near-earth plasmasheet starts thinning and the dipolar magnetic fields are stretched into tail-like fields. At substorm expansion phase, in the midnight sector there is a sudden brightening of the discrete auroral arcs, and their rapid poleward advancement (see Figure 10). In the near-earth magnetosphere the stretched tail-like configuration relaxes abruptly to a dipolar-like field geometry in association with thickening of the plasma sheet and earthward injection of energetic particles leading to the ring current formation. It is believed that the cross-tail current is suddenly interrupted and diverted to the polar ionosphere along magnetic field lines. The diverted current flows into the ionosphere on the morning side of the tail, then flows across the auroral ionosphere as an intensified westward electrojet and closes back into the magnetosphere by flowing upward along the field lines on the dusk side of the tail. This pattern of diverted current flow is known as the substorm current wedge [*McPherron et al.*, 1973; *Baumjohann*, 1986]. The recovery phase begins when the poleward expansion of the auroral bulge halts and the auroras start receding equatorward as shown in Figure 10 [*Akasofu et al., 1966]*. The plasmasheet suddenly thickens with fast field-aligned plasma flows in the plasma sheet boundary layers, the B_z component of the magnetic field increases and the strength of high-latitude currents and auroral luminosity decreases. 'l'he important events occuring during the three phases of the substorms are summarized in Figure 11.

3.3 Substorm Models

Several models have been proposed for the substorm phenomena based on the nature of solar wind energy input and that of the stored energy in the magnetosphere [*Kan et al.*, 1991]. Several statistical studies have shown that substorms clearly have both directly driven and loading - unloading components. Studies based on linear prediction filtering technique indicate that the typical time scales for the driven and loading-unloading processes are about 2(I minutes and 1 hour respectively.

3.3.1 Near Earth Neutral Line Model

The *near-earth neutral line (* NENL*)* model, also known as reconnection *model* [*Hones*, 1979], treats the substorm phenomenon as a *loading-unloading process*. It describes the growth phase as clue to enhanced dayside magnetic reconnection which leads to a larger tail size and thinning of the plasma sheet. The magnetic energy stored in the magnetotail is released explosively through a magnetic reconnection process in the vicinity of a newly formed neutral line in the near-earth tail region (at about 10 - 20 R_E down-stream). The neutral line formation leads to the disruption (the actual mechanism somewhat uncertain) of the cross-tail current in the vicinity of the neutral line, and to the severence of the plasmasheet to produce a plasmoid. The scenerio of events for the near-cart h neutral line model is shown in Figure 12. This picture of the substorm can explain many features connected with substorm activity.

3.3.2 Current Disruption Model

The *current disruption model* treats the substorm as a process *directly driven* by the solar wind [*Akasofu*, 1972]. According to this model, the solar wind energy input (equivalent to the power of the SM dynamo) directly controls the response of the magnetosphere such as the magnetospheric energy dissipation rate. When the solar wind energy input exceeds some critical value $\sim 10^{18}$ ergs s^{-1}, magnetospheric convection alone is unable to dissipate this much energy. Therefore the cross-tail current is disrupted and diverted to the ionosphere, along the magnetic field lines where it is dissipated efficiently. The resulting current circuit forms the substorm current wedge [*McPherron et al.*, 1973]. This is identified as substorm onset. It is commonly assumed that a sudden increase in anomalous resistivity due to a cross-field current instability is the likely cause for the current disruption [*Lui et al.*, 1992]. Particle injection results from the collapse of stretched field lines as a result of current disruption. The deflation of the plasmasheet is communicated downstream by the launching of a rarefaction wave, causing plasma sheet thinning further downstream of the current disruption region. The main sequence of event visualized under this model and shown in Figure 13 [*Siscoe*, 1993].

3.4 Status of Substorm Research

'I'he near-earth neutral line (NENL) model is considered to be the most successful as most of the substorm features can be fitted nicely in its framework. Magnetic reconnection, its dynamical principle, appears to be a universal process. On the other hand, current disruption seems to be an idea seeking a physical mechanism. Recent results on 31) MHD simulation of magnetotail evolution initiated by a sudden occurrence or increase of spatially localized resist ivity indicate that localized anomalous resisitivity can produce only localized effects on the cross-tail current, and it does not involve a reduction of the total cross-tail current [*Hesse and Birn*, 1994]. Hence it appears unlikely that an increase in anomalous resistivity in the magnetotail could lead to the global developement of a substorm current wedge. However, there is a major difficulty in the near- earth neutral line model related to the formation of a near-earth substorm neutral line which is tile most crucial point of this model. So far the predicted signatures of the substorm neutral line have not been found unambiguously earthward of $20 R_E$ despite the rather overwhelming evidence of substorms typically being initiated there [*Lui*, 1991].

It has been suggested that the substorms neutral line may be formed due to tearing mode, especially the ion tearing mode instability in the plasmasheet [*Coppi et al.*, 1966; *Schindler*, *1972, 1974, 1980; Galeev and Zelenyi, 1976; Lakhina and Schindler*, 1988; *Lakhina*, 1992a,b, 1994]. However, the tearing mode instability tends to get 'stabilized by the adiabatic electrons in the presence of a normal component, B_n, of the magnetic field [*Lembege and Pellat*, 1982]. Recently it has been suggested that the forced thin current sheet formed during growth phase of the substorm [*Fairfield et al.*, 1984; *Mitchell et al.*, 1990; *Pulkkinen et al.*, 1991; *Schindler and Birn*, 1993] might become ion tearing unstable [*Burkhart et a/.*, 1992a,b; *Burkhart et al.*, 1993; *Hesse and Winske*, *1993; Pulkkinen et al., 1994; Sanny et al., 1994]*, and thus may lead to substorm onset. *Lakhina* [1993b,c] has investigated disruption of such forced thin current sheets in astrophysical plasmas by ion tearing mode instability [Figure 14]. 'l'he forced thin current sheets formed during growth phase of the substorm could be unstable against ion tearing mode instability provided the the trapped electron population density is less than about 10- 20 % of the total electron number density [Figure 15]. 'lTherefore a process which can scatter electrons is required for the tearing mode instability to grow and the spontaneous reconnection to occur in the magnetotail.

There are some observations which indicate that the sequence of geomagnetic substorms is preceded by and well correlated with solar wind magnetic disturbances [*Akasofu*, *1980; Meloni et al.*, 1982; *Baker et al.*, 1983]. Furthermore, the energy released during substorms also appears to be well correlated with solar wind disturbances [*Akasofu*, *1981]*. Such observations have lead to a view that the solar wind magnetosphere coupling during disturbed periods is probably through the process of a driven or forced reconnection [*Sato and Hayashi*, *1979; Sato and Hasegawa*, *19S2; Walker and Sate, 1984]*.

In the forced or driven reconnection process, reconnection is induced by external means through perturbations at the boundaries. In contrast, spontaneous reconnection depends only on the internal state of the system, for example, the tearing mode instability in the neutral sheets. Driven reconnection has been studied analytically in a slab plasma model under different boundary conditions by using the magnetohydrodynamic (MHD) formalism [*Hu*, 19S3; *Zelenyi and Kuznetsova*, 1984; *Hahm and Kulsrud*, 1985; *Shivamoggi*, 1987].

The process of driven magnetic reconnection has been suggested as a possible mechanism to trigger substorm onset [*McPherron et al.*, 1986; *Horton and Tajima*, 19SS; *Pritchett et al.*, 1986;

Lakhina, 1992b]. *Lakhina* [1992b] has given a kinetic theory for driven reconnection in the Earth's magnetotail [Figure 16]. Driven reconnection can occur in two forms, namely, exponential type reconnection similar to the ion tearing mode, and bursty type reconnection which is short lived but occurs typically at rate much faster than the ion tearing growth rate [Figure 17]. Quasi-static perturbations in the solar wind energy input or pressure pulses are found to be most effective to initiate driven reconnection in the magnetotail. Bursty type reconnection cannot excite the regular substorm expansion phase as such, but it can produced bulk flows lasting for about a minute or two [*Lakhina*, 1996]. Hence, bursty driven reconnection appears to be a likely candidate for the generation of bursty bulk flows observed in the plasmasheet region. At the same time it provides a physical mechanism for the pseudobreakups or pseudo-substorm onsets [*Ohtani et al.*, 1993; *Russell et al.*, 1994]. Recent observations of bursty bulk flows in the inner central plasma sheet [*Baumjohann*, 1993; *Angelopoulos et al.*, 1992, 1994] provide a strong support for the bursty reconnection being operative in the magnetotail.

Büchner and Zelenyi [1987] proposed that chaotic electron motion might act similar to pitch angle scattering in destabilizing collisionless tearing mode [*Coroniti*, 1980] in the magnetotail leading to substorm onset. They replaced the pitch angle scattering with changes in $\Delta\mu$, the instantaneous magnetic moment in the midplane. They used the magnetic moment diffusion in place of energy diffusion for the tearing mode. They showed that the tearing mode can be unstable when $\kappa_e \simeq 1$, where $\kappa_e = (R_c/\rho_n)$, with R_c as the maximum radius of curvature, and ρ_n as the Larmor radius for electrons. It is interesting to point out that κ_e can decrease from $\kappa_e >> 1$ to $\kappa_e \simeq 1$ as the magnetotail becomes thinner, and thus it can possibly provide a transition from stability to instability. However, *Lui et al.* [1992] have found $\kappa_e \simeq$ 4-10 just prior to current disruption in the tail, and conducted that their data do not support the substorm onset condition $\kappa_e \simeq 1$. Recently, *Pritchett* [1994] has studied the effect of electron dynamics on collisionless reconnection in two-dimensional magnetot ail configuration by particle simuation. He claims that for the case of $\kappa_e << 1$, i.e., the regime where electrons are weakly chaotic, ion tearing mode is stabilized when $k\rho_n < 1$, a condition which is generally satisfied.

Considerable efforts are being devoted to the question of destabilization of tearing modes in the magnetotail. Several effects have been found which can potentially increase the tearing growth rates, for example the development of pressure anisotropy [*Chen and Palmadesso*, 1984], the presence of shear flow in the plasma sheet boundary layer [*Lakhina and Schindler*, 1983, 1988], coalescense of magnetic islands [*Richard et al.*, 1989], and external driving [*Horton and Tajima*, 19SS; *Lakhina*, 1992 b]. However, destabilization of the tearing mode in the magnetotail is a very controversial topic, and the reader can refer to *Pellat et al.* [1991] and *Kuznetsova and Zelenyi* [1991] for further details.

It has been realized that some aspects of nonlinear particle dynamics in the magnetotail could be playing an important role in the stability and evolution of the magnetotail in response to solar wind forcing. Recent studies from the dynamical point of view have shown that the particle motion in the magnetotail is nonintegrable and that the phase space is partitioned into disjoint regions occupied by dynamically distinct classes of orbits. 'l'he separation of time scales between these distinct regions of phase space has lead to the concept of differential memory. *Chen and Palmadesso* [1986, 19S7] have suggested that non-Maxwellian distributions generated by the process of differential memory can lead to enhancement of the growth rate of the collisionless tearing mode.

The suggestion that the Lyapunov exponent, which measures the rate of exponential divergence of nearby orbits, could be used as an effective collision frequency for the collisionless plasma has lead to the concept of collisionless chaotic conductivity [*Martin*, 19S6; *Büchner and Zelenyi*, 19S7; *Horton and Tajima*, 199o, 1991]. This could have interesting implications for particle acceleration and for the excitation of tearing modes in the magnetotail. Further, the effective trapping time of stochastic orbits plays an important role in differential memory, and leads to a novel phase space resonance effect [*Burkhart and Chen*, 1991].

Various correlation studies based on linear prediction filtering technique, the phase space reconstruction techniques and the analog models all show that the complex solar wind - magnetosphere ionosphere system is strongly nonlinear and dissipative. This system can be driven to chaotic behaviour with low dimensionality when the solar wind driving is strong enough [*Lakhina*, 1994; *Klimas et a/.*, 1996]. Concerted efforts involving new observational and data analysis techniques, theory and computer simulation techniques, e.g., MHD [*Birn and Hones*, 1981; *Birn and Hesse*, 1991; *Walker et al.*, 1982; *Ogino et* al., 1990] and particle simulations [*Zwingmann et al.*, 1990] are needed to better understand the complex processes related to both spontaneous and driven magnetic reconnection as well as the formation and disruption of forced current sheets in the magnetosphere, and to assess their role in the solar wind - magnetosphere - ionosphere coupling.

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REFERENCES

Akasofu, S.1., Meng, C.I. and Kimball, 1). S.: 1966, Dynamics of the aurora, 6, Formation of patches and their eastward motion, *J. Atmos. Terr. Phys.*, 28, 505 - 511.

Akasofu, S.1.: 1972, Magnetospheric substorms : a model, in *Solar Terrestrial Physics*, Part III, edited by E. R. Dryer, p.131, I). Reidel, Norwood, Mass.

Akasofu, S. I., The solar wind magnetosphere energy coupling and magnetospheric dist urbances, *Planet. Space Sci.*, *28*, 495, 1980.

Akasofu, S. I., Energy coupling between the solar wind and the magnetosphere, *Space Sci. Rev.*, *28*, 121, 1981.

Angelopoulos, V., Baumjohann, W., Kennel, C. II'., Coroniti, F. V., Kivelson, M. G., Pellat, R., Walker, R, J., Lühr, H., and Paschmann, G: 1992, Bursty bulk flows in the inner central plasma sheet, *J. Geophys. Res.*, 97, 4027-4039.

Angelopoulos, V., Sergeev, V. A., Mitchell, D. G., Reeves, G. D., Russell, C. T., and Singer, H. J.: 1994, Multi-point study of bursty bulk flow events during a sequence of small substorms, *Proc. international Conference on Substorms - 2,* University of Alaska, Fairbanks, March 7-11, 1994.

Arnoldy, R. L., Signature in the interplanetary medium for substorms, *J. Geophys. Res. 76*, 5189, 1971.

Baker, D. N., R. I). Zwickl, S. J. Smith and S. 1. Akasofu, An ISEE 3 high time resolution study of interplanetary parameter correlations with magnetospheric activity, *J. Geophys. Res.*, *88*, 6230, 1983.

Baumjohann, W.: 1986, Some recent progress in substorm studies, *J. Geomagn. Geoelectr.*, 38, 633-651.

Baumjohann, w.: 1993, The near-earth plasma sheet: An AMPTE/IRM perspective, *Space Sci. Rev.*, 64, 141 - 163. *J. Geomagn. Geoelectr.*, 38, 633-651.

Biernat, II. K., M. F. Heyn, R. P. Rijnbeck, V. S. Semenov, and C'. J. Farrugia, Reconnection at the Earth's dayside magnetopause in tile presence of sheared flows and skewed fields, *Ann. Geophys.*, *8*, 69, 1990.

Birn, J. and E. W. Hones, Jr., Three dimensional computer modelling of dynamic reconnection in the geomagnetic tail, *J. Geophys. Res.*, *86*, 6802, 19S1.

Birn, J. and M. Hesse, Substorm current wedge and field aligned currents in MHD simulations of magnetotail reconnection, *J. Geophys. Res. 96*, 1611, 1991.

Burkhart, G. R., J. F. Drake, P. B. Dusenbery, and T. W. Speiser, A particle model for magnetotail neutral sheet equilibria, *J. Geophys. Res.*, 9'7, 13,799, 1992a.

Burkhart, G. R., J. F. Drake, P. B. Dusenbery, and T. W, Speiser: 1992b, Ion tearing in a magnetotail configuration with an embedded thin current sheet, *J. Geophys. Res.*, 97, 16,749 - 16756.

Burkhart, G. R., Dusenbery, P. B., Speiser, T. W. and Lopez, R. E.: 1993, Hybrid simulation of thin current sheets, *J. Geophys. Res.*, 98, 21373-21390.

Burkhart, G. R., and Chen, J.: 1991, Differential memory in the Earth's magnetotail, *J. Geophys. Res.*, 96, 14,033-14,049.

Büchner, J., and L. M. Zelenyi, Chaotization of the electron motion as the cause of an internal magnetotail instability and substorm onset, *J. Geophys. Res.* 92, 13456, 19S7.

Chen, J., and P. Palmadesso, Tearing instability in an anisotropic neutral sheet, *Phys. Fluids, 27*, 1198, 19s4.

Chen, J. and Palmadesso, P. J.: 1986, Chaos and nonlinear dynamics of single-particle orbits in a magnetotail like magnetic field, *J. Geophys. Res.*, 91, 1499 - 1508. (correction, *J. Geophys. Res.*, 91, 9025, 19S6).

Chen, J., and Palmadesso, P. J.: 1987, Non-Maxwellian free-energy generation in the magnetot ail due to chaotic particle motion, in *Magnetotail Physics*, edited by A.T.Y. Liu, p 321, The John Hopkins University Press, Baltimore, hid.

Coppi, B., G. Laval, and R. Pellat, A model for the influence of the earth magnetic tail on geomagnetic phenomena, *Phys. Rev. Lett, 16*, 1207, 1966.

Dungey, J. Mr., Interplanetary magnetic field and the auroral zone, *Phys. Rev. Lett.*, *6*, 47, 1961.

Fairfield, D. H.: 1984, Magnetotail energy storage and the variability of the magnetotail current sheet in *Magnetic Reconnection in Space and Laboratory Plasmas*, edited by E.W. Hones, Jr., pp. 168 - 177, *Geophys. Monogr.*, vol. 30, AGU, Washington, D. C.

Galeev, A. A. and L. M. Zelenyi, Tearing instability in plasma configurations, *Sov. Phys. JETP*, Engl. Transl., *43*, 1113, 1976.

Gonzalez, W, D., Joselyn, J. A., Kamide, Y., Kroehl, H. W., Rostoker, G., Tsurutani, B. T., and Vasyliunas, V. M.: 1994, What is a geomagnetic storm?, *J. geophys. Res.*, 99, 5771 -,5792.

Haerendel, G., G. Paschmann, N. Sckopke, H. Rosenbauer, and P. C. Hedgecock, The frontside boundary layer of the magnetosphere and the problem of reconnection, *J. Geophys. Res., 83*, 3195, 1978.

Haerendel, G., and G. Paschmann, Interaction of the solar wind the dayside magnetosphere, in *Magnetospheric Plasma Physics*, edited by A. Nishida, Center for Academic Publications Japan, p. 49, Tokyo, 1982.

Hahm, T. S., and R. M. Kulsrud, Forced magnetic reconnection, *Phys. Fluids, 28*, 2412, 1985.

Heikkila, W. J., Is there an electrostatic field tangential to the dayside magnetopause and neutral line, *Geophys. Res. Lett.*, 2, 154, 1975.

Hesse, M. and Birn, J.: 1994, MHD modelling of magnetotail instability for localized resistivity, *J. geophys. Res.*, *99*, *8565-8576*.

Hesse, M. and Winske, D.: 1993, Hybrid simulation of collisionless ion tearing, *Geophys. Res. Lett.*, 20, 1207-1210.

Heyn, M. F., H. K. Biernat, R. P. Rijnbeck, and V. S. Semenov, The structure of reconnection layers, *J. Plasma Phys., 40, 235*, 1988.

Ho, C. M., B. T. Tsurutani, E. J. Smith and W. C. Feldman, A detailed examination of an x-line region in the distant tail: ISEE-3 observations of jet flow, Bz reversals and a pair of slow shocks, *Geophys. Res. Lett., 21*, 3031, 1994.

Ho, C. and B. T. Tsurutani, Distant tail plasma jetting and Bz properties at slow mode shocks: a model of reconnection during northward IMFs, *Geophys. Res. Lett., 22*, 2977, 1995

Hones, E. W., Jr.: 1979, Transient phenomena in the magnetotail and their relation to substorms, *Space Sci. Revs.*, 23, 393-410.

Hones, E. W., Jr. (Ed.), *Magnetic Reconnection in Space and Laboratory Plasma, Geophys. Monogr. Ser., vol. 30*, AGU, Washington, D. C. 1984.

Horton, W. and T. Tajima, Linear theory of driven reconnection, *Geophys. Res. Lett.*, 17, 2741, 1988.

Horton, W., and Tajima, "1'.: 1990, Decay of correlations and the collisionless conductivity in the geomagnetic tail, *Geophys. Res. Lett.*, 17, 123 - 126.

Horton, W., and Tajima, T.: 1991, Collisionless conductivity and stochastic heating of the plasma sheet in the geomagnetic tail, *J. Geophys. Res.*, 96, 15,811 - 15,S29.

Hu, P. N., Fast reconnection of magnetic field lines in plasma, *Phys. Fluids,* 26, 2234, 1983.

Hudson, P. D., Rotational discontinuities in an anisotropic plasma, *Planet. Space Sci., 19,* 1693, 1971.

Kamide, Y. and Kroehl, H. W.: 1994, Auroral electrojet activity during isolated substorms at different local times: A statistical study, *Geophys. Res. Lett.*, 21, 3S9 -392.

Kamide, Y., W. Baumjohann, I. A. Daglis, W.D. Gonzalez, M. Grande, J.A. Joselyn, R.L. McPherron, J. I,. Phillips, G. G. I). Reeves, G./ Rostoker, A.S. Sharma, H. J. Singer, B. 'I'. Tsurutani and V.M. Vasyliunas, Current understanding of magnetic storms; storm/substorm relationships, *J. Geophys. Res., 102, 1997.*

Kan, J. R., Potembra, T. A., Kokubun S. and Iijima, T.: 1991, *Magnetospheric Substorms, Geophysical Monograph 64,* American Geophysical Union, Washington, D. C.

Klimas, A. J., D. Vassiliadis, I). N. Baker, and D. A. Roberts, The organized nonlinear dynamics of the magnetosphere, *J. Geophys. Res. 101*, 13,0S9, 1996.

Kuznetsova, M. M. and Zelenyi, L.M.: 1991, Magnetic reconnection in collisionless field reversals : The I-Universality of the ion tearing mode, *Geophys.* Res. *Lett.*, 18, 1825 - 1828.

Lakhina, G. S., and K. Schindler, Collisionless tearing modes in the presence of shear flow, *Astrophys. Space Sci. 89*, 293, 19S3.

Lakhina, G. S. and K. Schindler, The effects of plasmasheet boundary flows and plasma mantle flow on the ion tearing instability, *J. Geophys. Res. 93*, 8591, 1988.

Lakhina, G. S., Some theoretical concepts of magnetospheric substorms, *Memoirs of Geophysical Society of India, No. 24,* Bangalore, India, p. 307, 1992a.

Lakhina, G. S., A Kinetic theory of driven reconnection in the Earth's magnetotail, *J. Geophys. Res.*, 97, 2961, 1992b.

Lakhina, G. S., P. K. Shukla, and L. Stenflo, Ultralow-frequency fluctuations at the magnetopause, *Geophys. Res. Lett.*, 20, 2419, 1993.

Lakhina, G. S., Electrodynamics coupling between different regions of the atmosphere, *Current Sci.*, 64, 660, 1993a.

Lakhina, G. S., On the tearing instability of forced current sheets, *J. Geophys.* lies., 98, 17409, 1993b.

Lakhina, G. S., Disruption of forced current sheets in astrophysical plasmas, *Bull. Astr.* Sot. *India,* 21, 537, 1993C.

Lakhina, G. S., Solar wind-magnetosphere-ionosphere coupling and chaotic dynamics, Surveys *Geophys., 15*, 703, 1994.

Lakhina, G. S., A mechanism for the bursty bulk flows in the plasma sheet region, *International Conference on Substorms, ICS-3*, Versailles, France, May 13-17, 1996.

Lanzerotti, L. J., and D. J. Southwood, Hydromagnetic waves, in *Solar System Plasma Physics, Vol.* 3, edited by L. J. Lanzerot t i, C. F. Kennel, and E. N. Parker, p. 109, North-Holland Publishing Company, Amsterdam, 1979.

Lee, L. C., and Z. l?. Fu, A theory of magnetic flux transfer at the Earth's magnetopause, *Geophys. Res. Lett., 12*, 105, 1985.

Lee, L. C., Z. Ma, Z. F. Fu and A. Otto, Topology of mafnetic flux ropes and the formation of fossil flux transfer events and boundary layer plasmas, *J. Geophys. Res., 98, 3943,* 1993.

Lembege, B., and R. Pellat, Stability of a thick two-dimensional quasi neutral sheet, *Phys. Fluids*, *25*, 1995, 1982.

Levy, R. H., H. E. Petschek, ant] G. 1,. Siscoe, Aerodynamic aspects of the magnetospheric flow, *AIAA J., 2, 2065, 1964.*

Lui, A. T. Y., Lopez, R. E., Anderson, B. J., Takahashi, K., Zanetti, L. J., McEntire, R.W., Potemra, T.A., Klumpar, D.M., Greene, E.M. and Strangeway, R.: 1992, Current disruption in the near-Earth neutral sheet region, *J. Geophys. Res.*, 97, 1461 - 1480.

Lui, A. 'I'. Y.: 1991, A synthesis of magnetospheric substorm models, *J. Geophy. //es.*, **96**, 1849 - 1858.

Martin, R. F.: 1986, Chaotic particle dynamics near a two-dimensional magnetic neutral point with application to the geomagnetic tail, *J. Geophys. Res.*, 91, 11,985 - 11,992.

McPherron, R.I,., Russell, C.'l'. and Aubry, M.D.: 1973, Satellite studies of magnetospheric substorms of August 15, 1968, O. Phenomenological model for substorms, *J. Geophys. Res.*, 78, 3131-3149.

McPherron, R. L., Terasawa, '1'. and Nishida, A.: 1986, Solar wind triggering of substorm expansion onset, ıJ. Geomagn. Geoelectr., 38, 1098 - 1108.

Meloni, A., A. Wolfe, and L.J. Lanzerotti, On the relationship between interplanetary quantities and the global auroral electrojet index, *J. Geophys. Res., 87,* 119, 1982.

Mitchell, D. G., Williams, I). J., Huang, C. Y., Frank, L. A., and Russell, C. T.: 1990, Current, carriers in the near-Earth crosstail current sheet during substorm growth phase, *Geophys. Res. Lett., 17, 583-586.*

Morfill, G., and M. Scholer, Study of the magnetosphere using energetic solar particles, *Space Sci. Rev., 15, 267, 1973.*

Mozer, F. S., R. B. Torbert, U. V. Fahleson, C.-C. Fälthammar, A. Gonfalone, A. Pedersen, and C. T. Russell, Direct observation of a tangential electric field component at the magnetopause, *Geophys. Res. Lett., 6, 305, 1979.*

Nishida, A., T. E. Eastman, and E. W. Hones, Jr., Comparison of the magnetopause current layer with Alfvén wave, in *Magnetospheric Study 1979, Proc. Internat. Workshop on Selected Topics of Magnetospheric Physics, p. 344,* Tokyo, March 1979.

Ogino, T., R. J. Walker, and M. Ashour-Abdalla, Magnetic flux ropes in 3-dimensional MHD simulations, in *Physics of Magnetic Flux Ropes*, Geophys. Monograph 5S, edited by C. T. Russell, E. R. Priest and L. C. Lee, p.669, AGU, Washington D. C., 1990.

Ohtani, S., Anderson, B. J., Sibeck, I). G., Newell, P. T., Zanetti, I,. J., Potemra, '1'. A., Takahashi, K., Lopez, R. E., Angelopoulos, V., Nakamura, R., Klumpar, D. M., Russell, C. "I'.: 1993, A multi-satellite study of a pseudo-substorm onset in the near-earth magnetotail, *J. Geophys. Res.*, 98, 193545- 19367.

Otto, A, L.C. Lee, Z.W. Ma, Magnetic field and plasma properties associated with pressure pulses and magnetic reconnection at tile dayside magnetopause, *J. Geophys. Res., 100*, 14S95, 199.5.

Paschmann, G., B. U. O. Sonnerup, I. Papamastorakis, N. Sckopke, G. Haerendel, S. J. Bame, J. R. Asbridge, J. T. Gosling, C. 'l'. Russell and R. C.Elphic, Plasma acceleration at the Earth's magnetopause: Evidence for reconnection, *Nature*, 282, 243, 1979.

Pellat, R., Coroniti, F.V. and Pritchett, P.L.: 1991, Does ion tearing exist ?, *Geophys. Res. Lett.*, 18, 143-146.

Perreault, P., ant{ S.-I. Akasofu, A study of geomagnetic storms, *Geophys. J. R. Astr. Sot., 54*, 547, 1978.

Petschek, H. E., Magnetic filed annihilation, *NASA Special Publ., NASA - SP -50, p.* 425, 1964.

Schindler, K., *J. Geophys. Res.*, 79, 2803, 1974.

Pritchett, P. I,., Coroniti, F. V., Pellat, R. and Karimabadi, 11., Collisionless reconnection in a quasi-neutral sheet near marginal stability, *Geophys. Res. Lett.*, 16, 1269, 1989.

Pritchett, P. L., Effect of electron dynamics in collisionless reconnection in two-dimensional magnetotail equilibria, *J. Geophys. Res.*, 99, 5935, 1994.

Pulkkinen, T. I., Baker, I). N., Fairfield, I). 11., Pellinen, R. J. Murphrec, J. S. Elphinstone, R. D., McPherron, R. L., Fennell, J. F., Lopez, R. E., and Nagai, T., Modeling the growth phase of a substorm using the Tsyganenko model anti multi-spacecraft observations: CDAW-9, *Geophys. Res. Lett.*, 18, 1963, 1991.

Pulkkinen, T. I., Baker, I). N., Mitchell, I). G., McPherron, R. L., Huang, C. Y. and Frank, L. A.: 1994, Thin current sheets in the magnetotail during substorms: CDAW 6 revisted, *J. Geophys. Res.*, 99, 5793-5805.

Richard, R. L.,R. J. Walker, R. I). Sydora, and M. Ashour-Abdalla, The coalescence of magnetic flux ropes and reconnect ion in the magnetotail, *J. Geophys. Res.,* 93, 2471, 19S9.

Russell, C. T., and R. C. Elphic, Initial ISEE magnetometer results: magnetopause observations, *Space Sci.* Rev., 22, 681, 1978.

Russell, C. T., Ginskey, M., and Angelopoulos, V., The effect of sudden impulses on currents in the auroral ionosphere under northward IMF conditions: A case study, *J, Geophys. Res.*, 99, 17,617, 1994.

Sato, 'I'., and T. Hayashi, Externally driven magnetic reconnection and a powerful magnetic energy converter, *Phys. Fluids, 22*, 1189, *1979.*

Sate, '1'., and A. Hasegawa, Externally driven magnetic reconnection versus tearing mode instability, *Geophys. Res. Lett.*, 9, 52, 1982.

Sanny, J, McPherron, R. I,., Russell, C. T., Baker, D. N., Pulkkinen, T. I., and Nishida, A.: 1994, Growth phase thinning of the near-earth current sheet during the CDAW 6 substorm, J. *Geophys. Res.*, 99, 5805-.5816.

Schindler, K., A self consistent theory of the tail of the magnetosphere, in *Earth's Magnetospheric Processes,* edited by B. M. McCormac, p. 200,]). Reidel, Norwell, Mass., 1972.

Schindler, K., A theory of the substorms mechanism, *J. Geophys. Res.* '79, 2803, 1974.

Schindler, K., Spontaneous Reconnection, in Magnetic Reconnection in Space and Laboratory Plasmas, edited by E. W. Hones, Jr., p. 9, AGU, Washington, DC, 1984.

Schindler, K., and A. Otto, Resistive instability, in Physics of Magnetic Flux Ropes, edited by C. 'I'. Russell, E. R. Priest, and I,. C. Lee, *Geophys. Monogr. Ser., Vol.* 58, p. 51, AGU, Washington, Dc, 1990.

Schindler, K. and Birn, J.: 1993, On the cause of thin current sheets in the near-earth magnetotail and their possible significance for magnetospheric substorms, *J. Geophys. Res.*, 98, 15477 - 15486.

Scholer, M., Magnetic flux transfer at the magnetopause based on single X line bursty reconnection, *Geophys. Res. Lett., 15, 291, 1988.*

Scholer, hi., F'. M. Ipavich, G. Gloeckler, I). Hovestadt, and B. Klecker, Leakage of magnetospheric ions into the rnagnetosheath along reconnected field lines at the dayside magnetopause, *J. Geophys. Res., 86, 1299, 1981.*

Shivamoggi, B. K., Magnetic reconnection induced by perturbations on boundaries, *Phys. Fluids, 30*, 1228, 1989.

Sibeck, I)., A model for the transient magnetospheric response to sudden solar wind dynamic pressure variations, *J. Geophys. Res.*, 95, 2543, 1990. Sibeck, D., Transient events in the outer magnetosphere: Boundary waves or FTEs?, *J. Geophys. Res., 97, 4009,* 1992.

Sibeck, D., and M. F. Smith, Magnetospheric plasma flows associated with boundary waves and flux transfer events, *Geophys. Res. Lett.*, 19, 1903, 1992.

Siscoe, G.: 1993, Recent activity in substorm research, *Adv. Space Res.*, 13, No.4, 165-172.

Sonnerup, B. U. O, J. Ip, and B. G. Ledley, Electromagnetic structure of the magnetopause and boundary layer, in *Magnetospheric Boundary Layers, ESA SP-148*, edited by B. Battrick, p. 401, European Space Agency, Paris, 1979.

Sonnerup, B. U. O, and L. J. Cahill, Jr., Magnetopause structure and at titude from Explorer 12 observations, *J. Geophys. Res.* 72, 171, 1967.

Sonnerup, B. U. O, G. Paschmann, I. Papamastorakis, N. Sckopke, G. Haerendel, S. J. Bame, J. R. Asbridge, J. T. Gosling, and C. T. Russell, Evidence for magnetic field reconnection at the Earth's magnetopause, *J. Geophys. Res.* 86, 10049, 1981.

Sonnerup, B. U. O, Magnetic field reconnection at the magnetopause: An overview, in Magnetic Reconnection in Space and Laboratory Plasmas, edited by E. W. Hones, Jr., p. 92, AGU, Washington, DC, 1984.

Southwood, D. J., C. J. Farrugia, and M. A. Saunders, What are flux transfer events, , *Planet. Space Sci.,* 36, 503, 1988.

Speiser, T. W.: 1965, Particle trajectories in model current sheets, 1, Analytical solutions, *J. Geophys. Res.*, 70, 4219-4226.

Tsurutani, B. T., and C.-I. Meng, Interplanetary Magnetic Field Variations and Substorm Activity, *J. Geophys. Res., 77*, 2964, 1972.

Tsurutani, B. T. and W. D. Gonzalez, The interplanetary causes of magnetic storms: A review, in *Magnetic Storms,* edited by B. 'l'. Tsurutani, W. I). Gonzalez and Y. Kamide, AGU Monograph, Wash. D. C., 77, 1997.

Vampola, A. L., Access of solar electrons to closed field lines, *J. Geophys. Res. 76*, 3S, 1971.

Vasyliunas, V. hi., Theoretical models of magnetic field line merging, *Rev. Geophys., 13*, 303, 1975.

Walker, R. J., and T. Sate, Externally driven magnetic reconnection, in *Magnetic Reconnection in Space and Laboratory Plasmas, Geophys. Monogr. Ser.*, vol *30,* edited by E. W. Hones, Jr., p. 272, AGU, Washington, D. C., 1984.

Walker, R. J., Ogino, T. and Ashour-Abdalla, M.: 1987, A global magnetohydrodynamic model of magnetospheric substorms, in *Physics of Space Plasmas, SPI Conf. Proc. Reprint Ser.*, Vol. *7*. p. 235, Scientific Publication, Cambridge, Mass.

Williams, D. J., and L. A. Frank, ISEE 1 charged particle observations indivative of open magnetospheric field lines near the subsolar region, *J. Geophys. Res.* 85, 2037, 19S0.

Yang, C. K., and B. U. O. Sonnerup, Compressible magnetopause reconnection, *J. Geophys. Res. 82*, 699, 1977.

Zelenyi, L. M., and M. M. Kuznetsova, Large-scale instabilities of the plasmasheet driven by particle fluxes at the boundary of the magnetosphere, *Sov. J. Plasma Phys. 10*, 190, 1984.

Zwingmann, W., J. Wallace, K. Schindler, and J. Birn, Particle simulation of magnetotail configuration, *J. Geophys. Res. 95*, 20S77, 1990.

Figure Captions

Fig. 1: Schematic illustration of a 3 D view of the Earth's magnetosphere. Small arrow's indicate the direction of the magnetic field lines. Thick arrows show the direction of electric currents. Various current systems present in the magnetosphere are indicated.

Fig. 2: Schematics of two models for the Earth's magnetosphere. (a) Closed model for the magnetosphere model based on strict application of frozen-field theorem. (b) Open magnetospheric model which allows reconnection between the interplanetary magnetic field and the geomagnetic field at the dayside magnetopause current sheet. 'l'he magnetic flux is eroded from the dayside and transported to the nightside by the solar wind. Stored magnetic energy in the magnetotail is explosively released during substorms, believed to be triggered by the onset of reconnection at the near Earth neutral line.

Fig. 3: A schematic view of the steady-state reconnection configuration at the magnetopause for antiparallel IMF and geomagnetic field lines (shown as solid lines). The magnetopause (MP) is depicted as a current layer of finite thickness, with an adjoining boundary layer (BL). Magnetosheath and magnetosphere are located to the left and right of the magnetopause, respectively. Those magnetosheath and magnetospheric field lines connected to the separator (or X-line) for the outer (S1) and inner (S2) separatrix, respectively. The normal component of the magnetic field, B_n, is negative north of the separator and positive south of it. Dashed lines are streamlines and the heavy arrows indicate the plasma flow speed outside and inside the magnetopause. The reconnection electric field, $\mathbf{E}_t$, is aligned with the magnetopause current I (taken from it Sonnerup et al., 1981].

Fig. 4: ShowS five minutes of electric and magnetic field data recorded by ISEE1 in a reference frame oriented along the average magnetopause. During this traversal the magnetopause passed back and forth over the spacecraft. The error bars in the electric field data are the standard deviations of a single point in the sine wave least square fit of six seconds of data. E_y' is the tangential component of in the dawn-dusk direction. The magnetopause motion has not been removed from the data (taken from *Mozer et al.*. 1979].

Fig. 5: Shows polar plots of the magnetic field during an OGO-5 crossing of the magnetopause. Left-hand figure shows the field component B_1 and B_2 tangential to the magnetopause, and the right-hand figure shows the nearly constant magnetic field component B_3 normal to tile magnetopause. The magnetic field is represented in units of nano-tesla (nT). The segment $A_1 - A_2$ denotes the rotational discontinuity (taken from *Sonnerup and Ledley*, 1979].

Fig. 6: Shows polar plots of the magnetic field B (top) and plasma flow velocity v (bottom) for the ISEE 1 magnetopause crossing on September 8, 1978. The coordinate system is obtained from minimum variance analysis. The k axix is along the outward directed magnetopause normal, the i, j planne is tangential to the magnetopause, with i and j axes approximately due north and west, respectively. 'l'he points marked (1) and (2) refer to the magnetosheath and the magnetosphere sides of the magnetopause. The vectors corresponding to the magnetopause current I and the inferred electric field $\mathbf{E}_t$ are also shown (taken from *Paschmann et al.*, 1979).

Fig. 7: Shows the results of a comparison between measured ΔV_{obs} and predicted A V_{th} tangent ial velocity enhancements across the magnetopause for 11 cases observed by ISEE 1 and 2. Each vector represents the measured velocity change, rotated around the normal in such a way that the predicted velocity change lies along the horizontal (dotted line) in each case. Vectors have been normalized such that the predicted vector has unit length, therefore in case of perfect agreement, the vectors should be horizontal and of unit length (taken from *Sonnerup et al.*, 1981).

Fig. 8: Shows the flux transfer events observed by ISEE 1 (heavy lines) ant] ISEE 2 (light lines) on November 8, 1977. The magnetic field data is shown in boundary normal coordinates. Verticle dashed lines indicate the time of flux transfer events. The events are characterized by normal component B_N undergoing a bipolar change, and the presence of hot electrons and ions of magnetospheric origin and cold flowing magnetosheath plasma (taken from *Russell and Elphic*, 1979).

Fig. 9: Schematic of a flux transfer event. The magnetosheath field lines, shown as slanted arrows, get connected with magnetospheric field lines, shown as vertical arrows, possibly off the lower edge of the figure. The connected flux tube is carried by the rnagnetosheath flow in the dddirection of large arrow. The magnetosheath field lines not connected to the magnetosphere drape over the connected flux tube and are swept up by its motion relative to the magnetosheath flow (taken from Russell *and Elphic*, 1979).

Fig. 10: Schematic diagram to show the development of both the auroral and polar magnetic substorms, from a quiet situation (a), an early epoch of the expansive phase (b), the maximum epoch of the substorm (c), to an early epoch of the recovery phase (cl). The region where a negative magnetic bay is observed is indicated by the line shade, and the region of a positive bay by the dotted shade (*after Akasofu et al. 1966; with permission from Pergamon Press*).

Fig. 11: Block diagram showing important events taking place during various phases of magne-

tospheric substorm (*taken from Lakhina, 1993a; with permission from Geological Society of India*).

Fig. 12: Schematic representation of changes of the magnetotail plasma sheet that are thought to occur during substorms. These are cuts along the midnight meridian plane of the tail. Earth is at left and a clot near the center of each picture represents a satellite at X = - 35 R_E and d Z = $\pm$ 1 R_E. Black lines are magnetic field lines and white arrows indicate plasma flow. A distant neutral line, N, is shown at X = -60 R_E and is though to be a quasi-permanent feature of the magnetotail though its distance is not really known and is probably quite variable. The fine hatching indicates the plasma sheet, which contains closed field lines 1 , 2, 3, 4 and is bounded by the "last closed field line", 5. Field lines 6 and 7 arc in the lobe, outside the plasmasheet (*taken from Hones, 1977; with permission from American Geophysical Union*).

Fig. 13: The four basic stages of the magnetospheric substorms as manifested in the polar ionosphere, the meridional magnetosphere, and the equatorial magnetosphere according to the current-disruption model (after *Siscoe, 1993; with permission from Pergamon Press).*

Fig. 14: Schematics of the two dimensional configuration of the earth's plasma sheet with an embedded forced current sheet at the center. 'l'he plasmasheet has a characteristic dimension of 2L and the forced current sheet (hatched region) has a half thickness of *a*. The r-component of the magnetic field has a value B_{xo} just outside the boundary of the inner current sheet (dashed horizontal line), and a value B_L in the lobe region. A uniform dawn to dusk electric field E_y is imposed on the plasma sheet. 'l'he forced current sheet has a finite B_n (after *Lakhina, 1993'6; with permission from American Geophysical Union*).

Fig. *15:* Variation of normalized growth rate $\gamma L/V_{ti}$ versus normalized wave numbers $\bar{k} = kL$ for ion tearing instability of the two dimensional magnetotail with an embedded current sheet. The plasma parameters are $\bar{a}_i = a_i/L =$ 0.25, $v_D/V_{ti} =$ *2.0*, $T_i/T_e = 10.0$, $\epsilon = B_n/B_{xo} = 0.1$, $\bar{z}_o = z_o/L$ = *0.3* and for $\eta =$ 0.0, 0.05, 0.1 for the curves 1, 2 and 3 respectively. Here η represents the fraction of trapped electron population in the inner sheet relative to the total electrons number density (*after Lakhina, 1993b; with permission from A merit-on Geoph ysical Union).*

Fig. 16: Schematic of the earth's magnetotail for the driven reconnection process. The plasmasheet has a characteristic dimension of 2 L in the Z-direction. The magnetopause boundary is situated at $Z = \pm a$. The solar wind- magnetosphere interaction perturbes the magnetopause boundary resulting in a distortion, δ, of the boundary. The singular layer is centred at Z = O and has a

width of 2δ. The external region extends from the singular layer boundary to the magnetopause boundary in both tail lobes. The perturbations at the magnetopause boundary could induce the process of driven reconnection in the magnetotail (*after Lakhina, 1992b; with permission from American Geophysical Union).*

Fig. 17: Variation of driven reconnection rate normalized with ion tearing mode instability growth rate versus normalized wavenumber $\tilde{k} = kL$ for the earth's magnetotail parameters: T_e/T_i = 0.1, a_i/L = 0.2, B_z/B_0 = 0.1 and for two values of the magnetopause boundary, namely *a/L* = 10 (solid curve), and a/L = 5 (dashed curves). The curves 1, 2 and 3 are for $\eta =$ 0.0, 0.2 and 0..5 respectively, where parameter η denotes the relative trapped electron population with respect to total electron number density. The process of driven reconnection occurs in two modes; the positive γ mode corresponds to the expotential type reconnection (which is similar to the ion tearing mode), and the negative γ mode corresponds to the bursty reconnection. The bursty reconnection is driven at a much faster rate as compared to the ion tearing modes but has a short duration of typically inverse of the reconnection rate (taken *from Lakhina, 1992b, with permission from American Geophysical Union).*

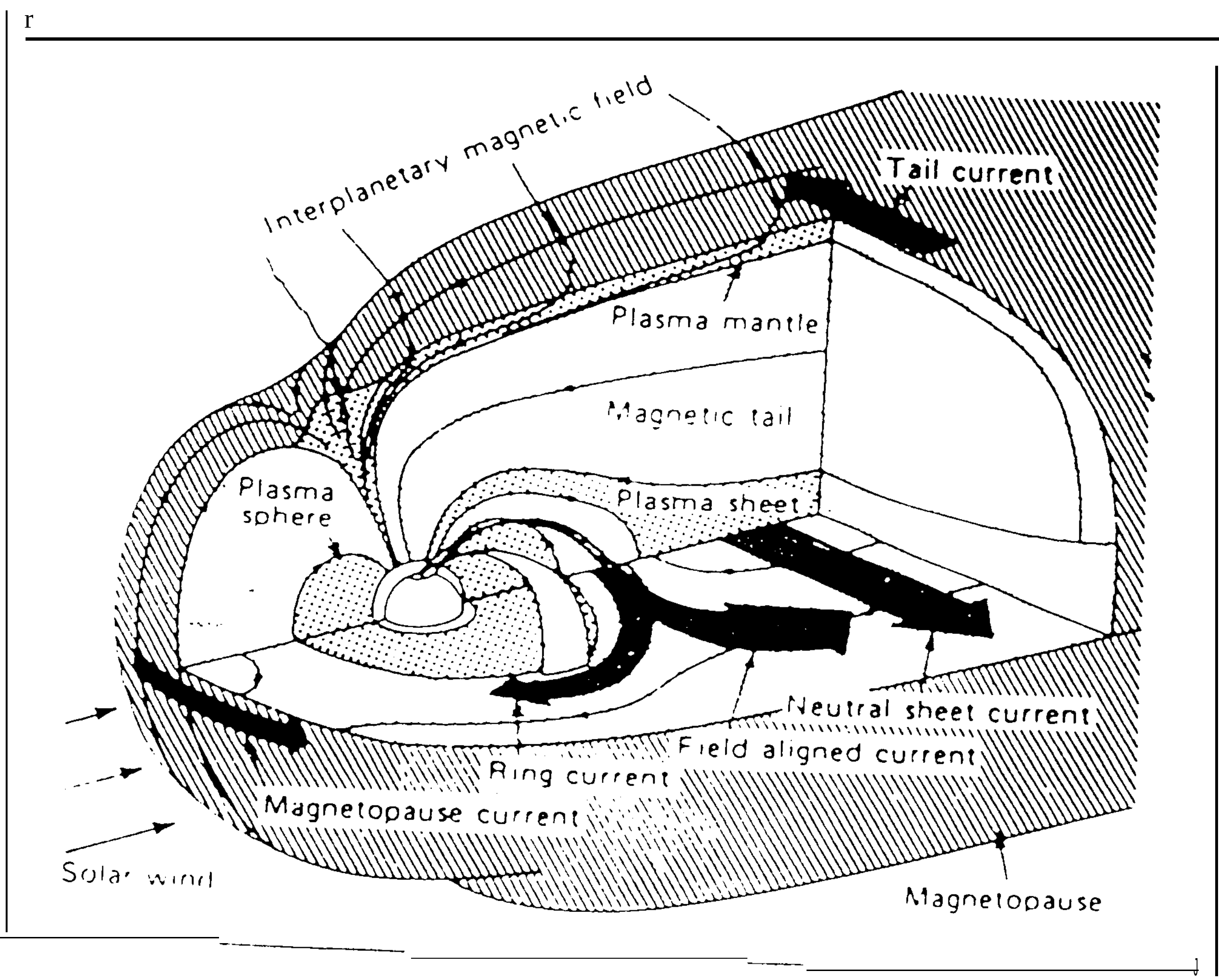

Interplanetary magnetic field
Tail current
Plasma mantle
Magnetic tail
Plasma sphere
Plasma sheet
Neutral sheet current
Field aligned current
Ring current
Magnetopause current
Solar wind
Magnetopause

Fig. 1

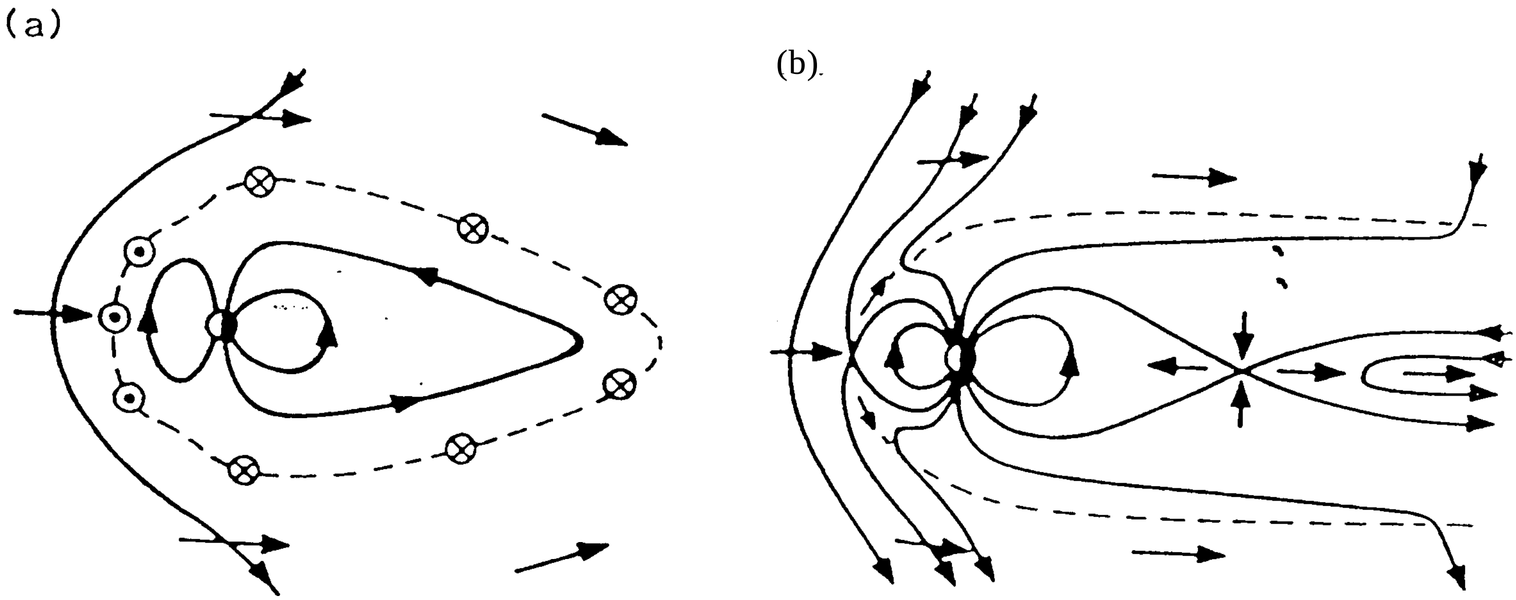


Fig. 2

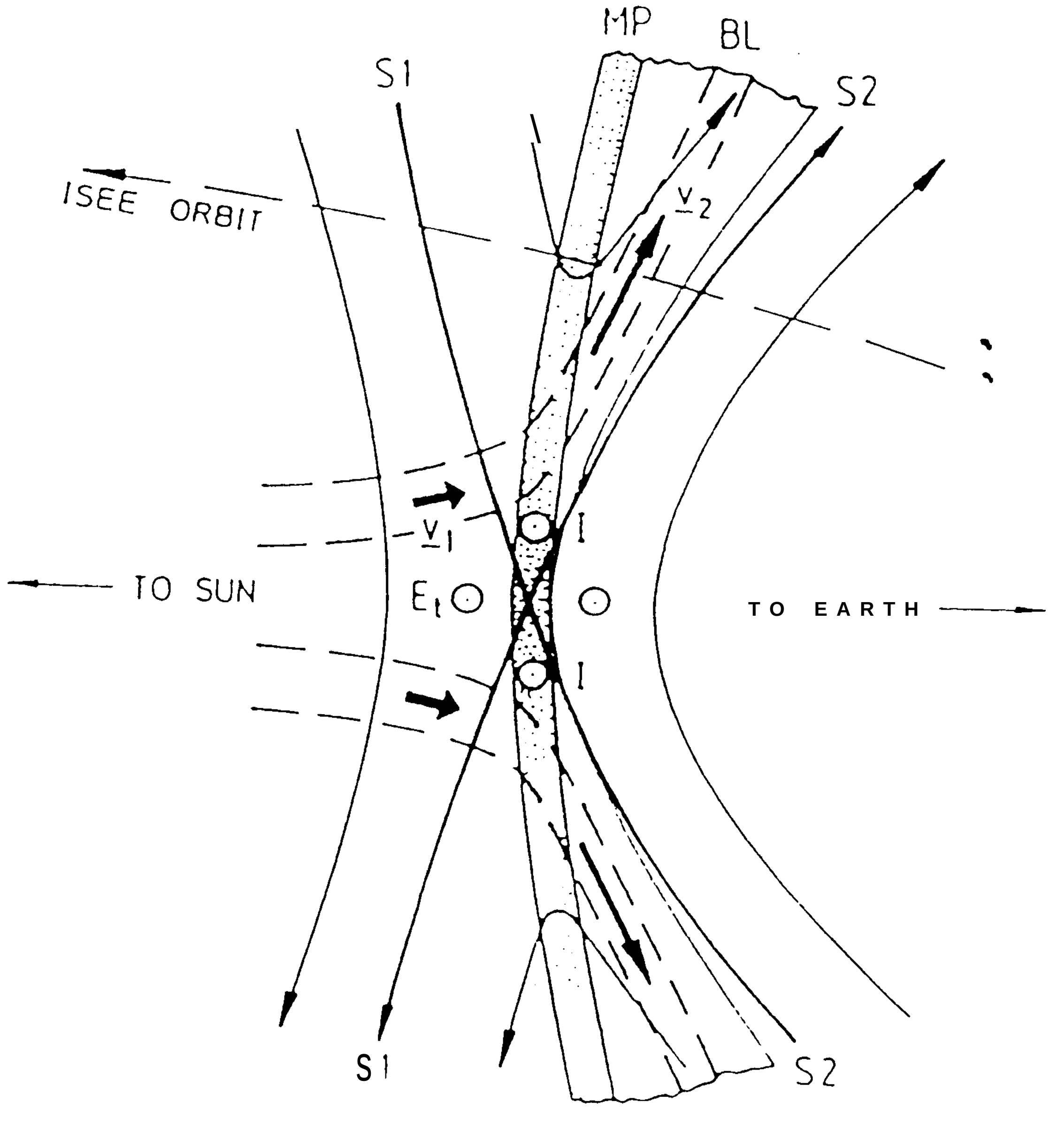

MP
BL
S1
S2
ISEE ORBIT
$\underline{v}_2$
$\underline{v}_1$
I
TO SUN
E_t
TO EARTH
I
S1
S2

Fig 3

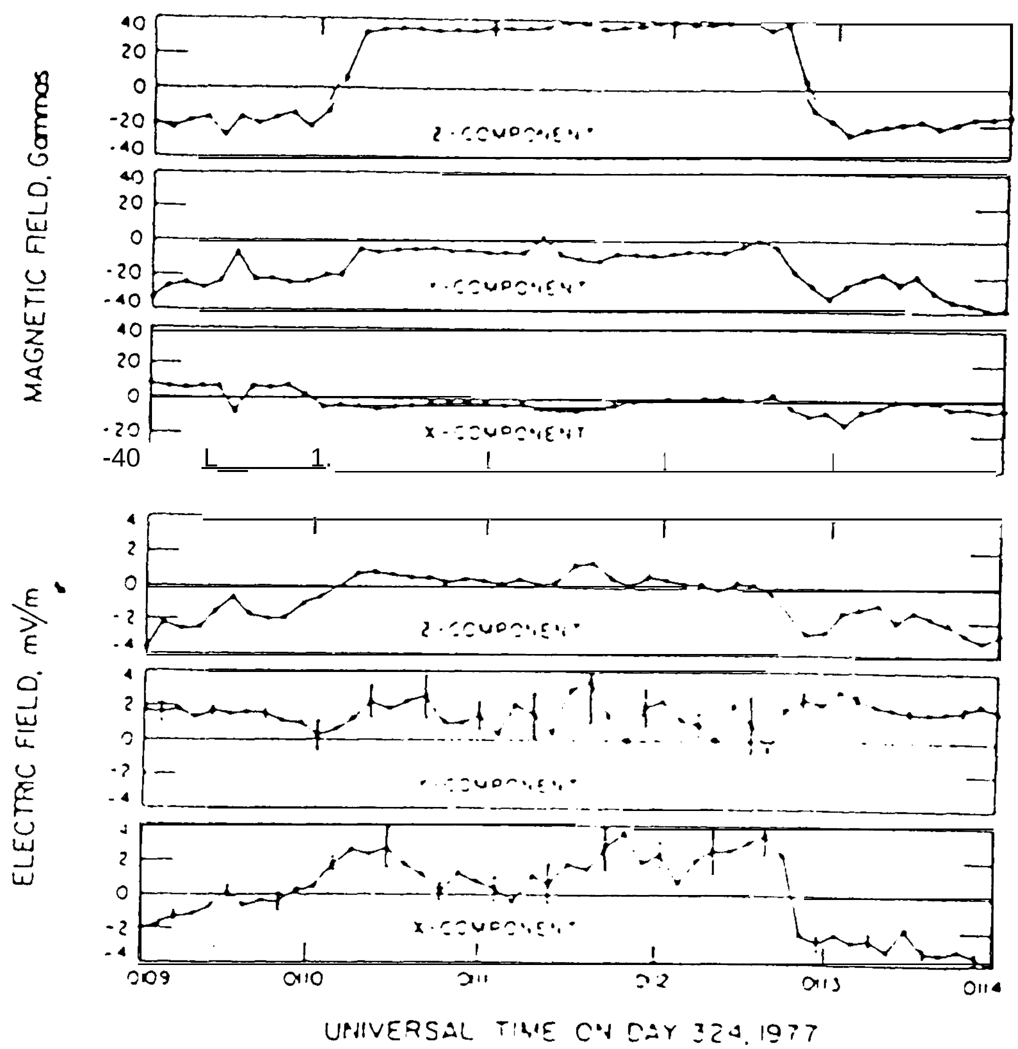
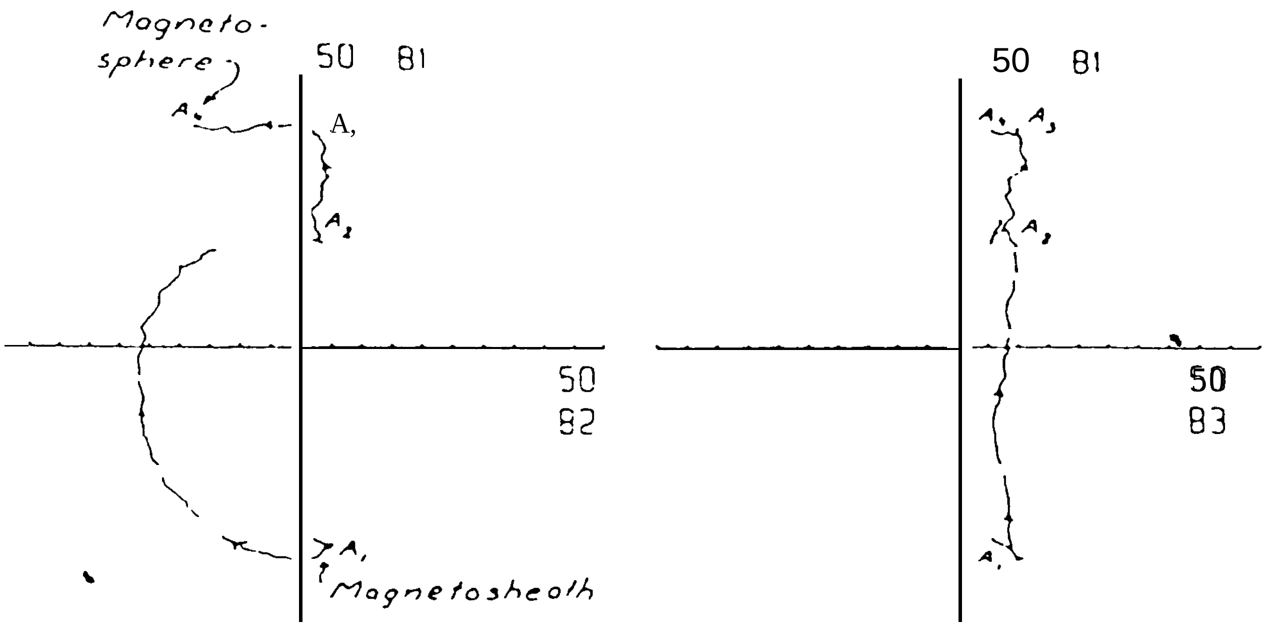
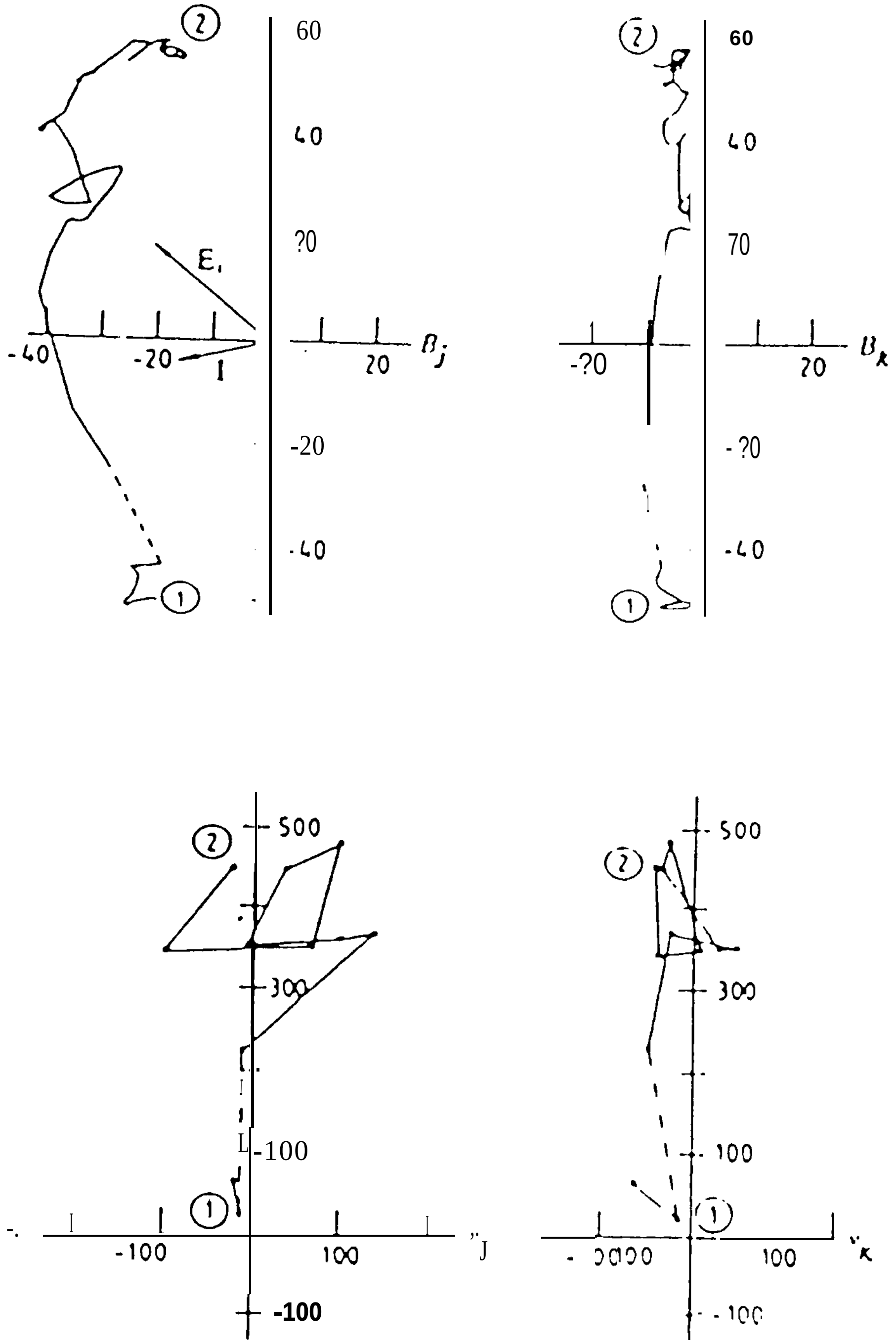

MAGNETIC FIELD, Gammas
Z-COMPONENT
Y-COMPONENT
X-COMPONENT
ELECTRIC FIELD, mV/m
0109
0110
0111
0112
0113
0114
UNIVERSAL TIME ON DAY 324, 1977

Fig. 4



68 03 27 18:18:56:34 UT

Fig 5



60
40
?0
E₁
-40
-20
20
B_j
-20
-40
60
40
70
-?0
20
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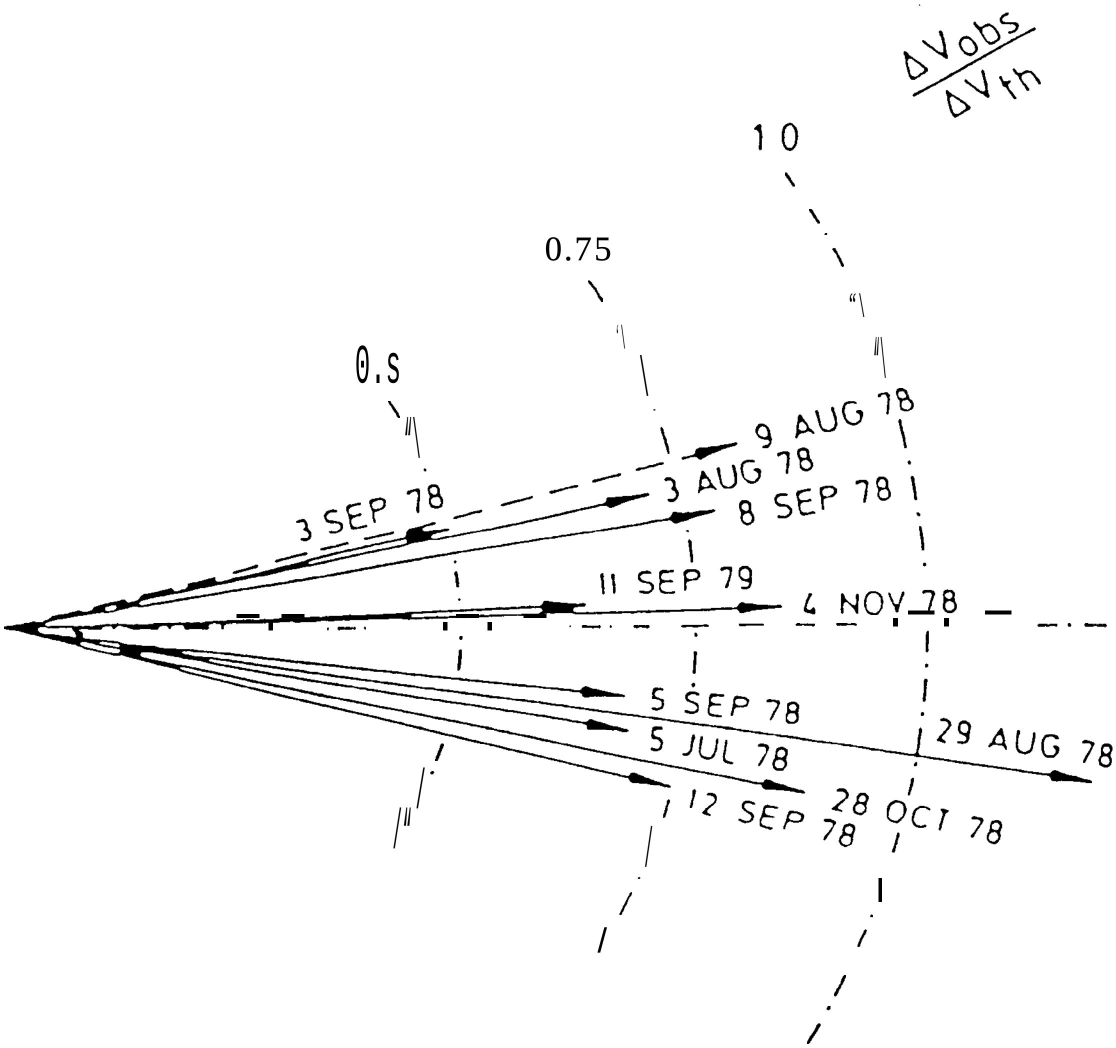
500
300
-100
-100
100
J
-100
500
300
100
100
-100

Fig 6



$\frac{\Delta V_{obs}}{\Delta V_{th}}$
1.0
0.75
0.5
9 AUG 78
3 AUG 78
3 SEP 78
8 SEP 78
11 SEP 79
4 NOV 78
5 SEP 78
5 JUL 78
29 AUG 78
12 SEP 78
28 OCT 78

Fig. 7

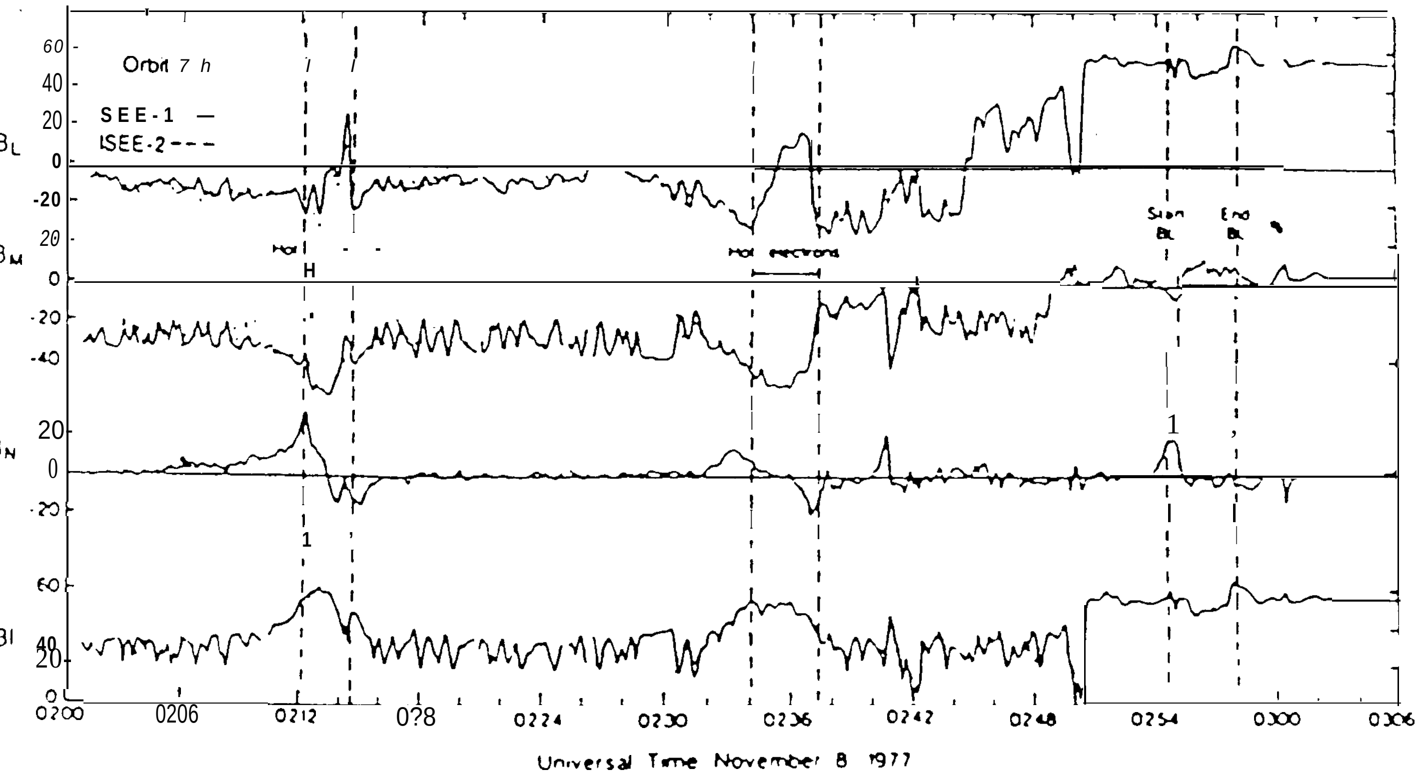

Orbit 7 h
SEE-1 —
ISEE-2 - - -
B_L
B_M
B_N
|B|
Hot electrons
Start BL
End BL
0200
0206
0212
0218
0224
0230
0236
0242
0248
0254
0300
0306
Universal Time November 8 1977

Fig. 2

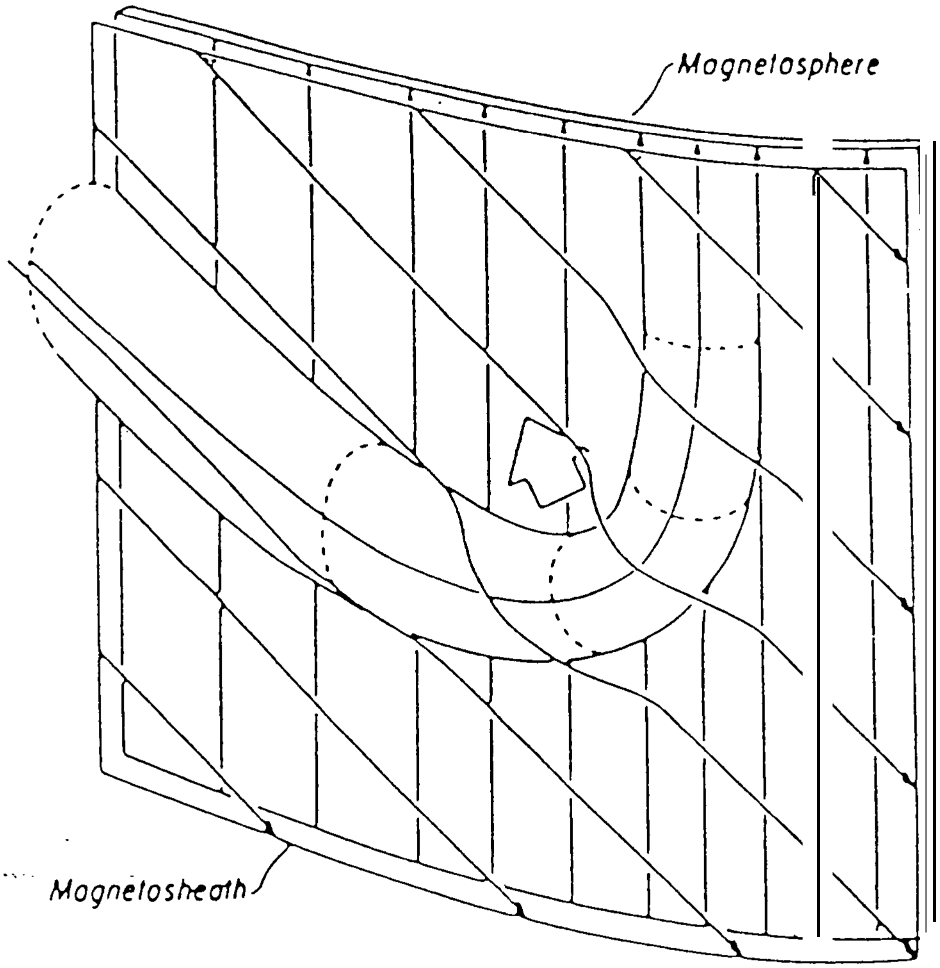


Fig. 9

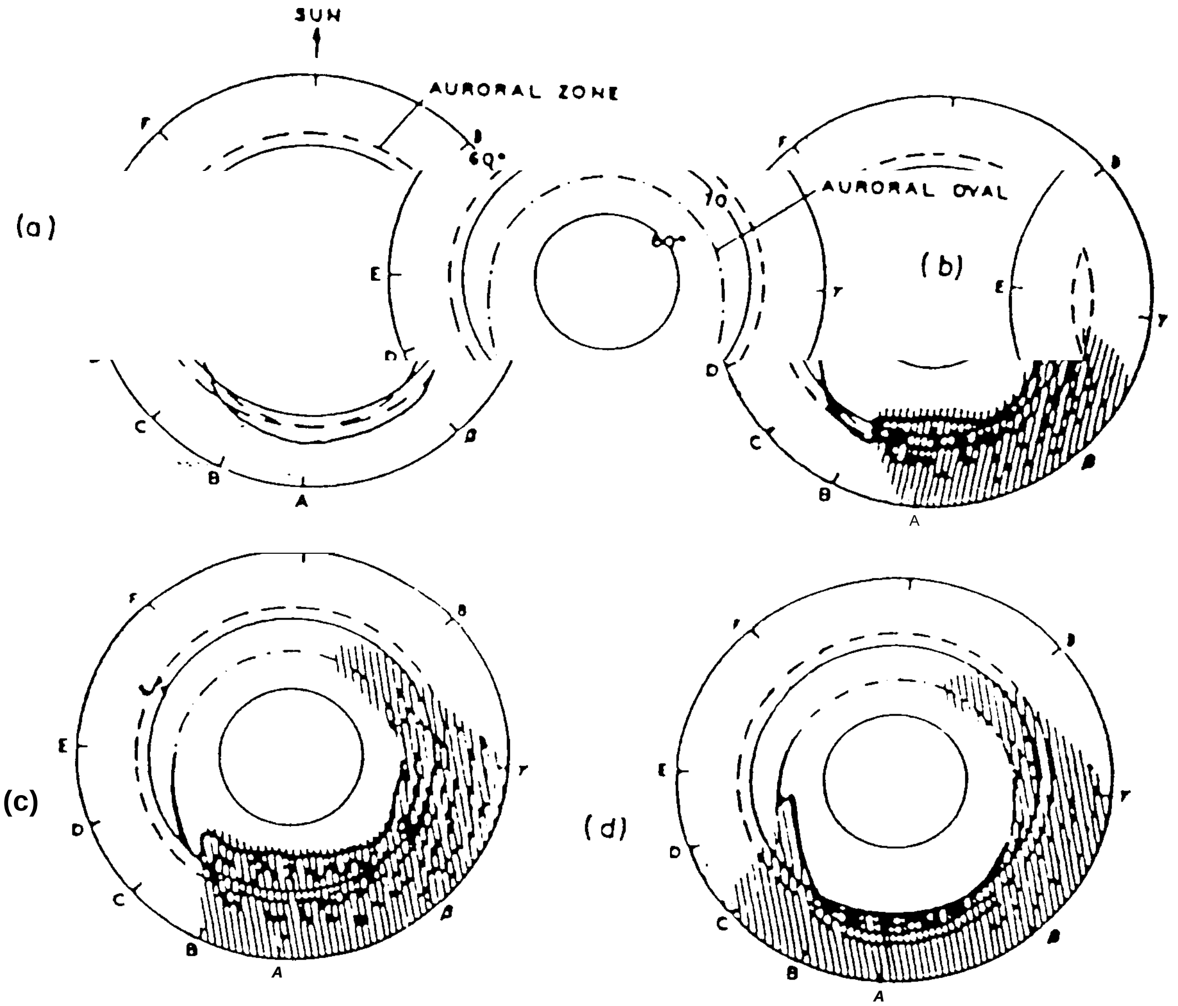
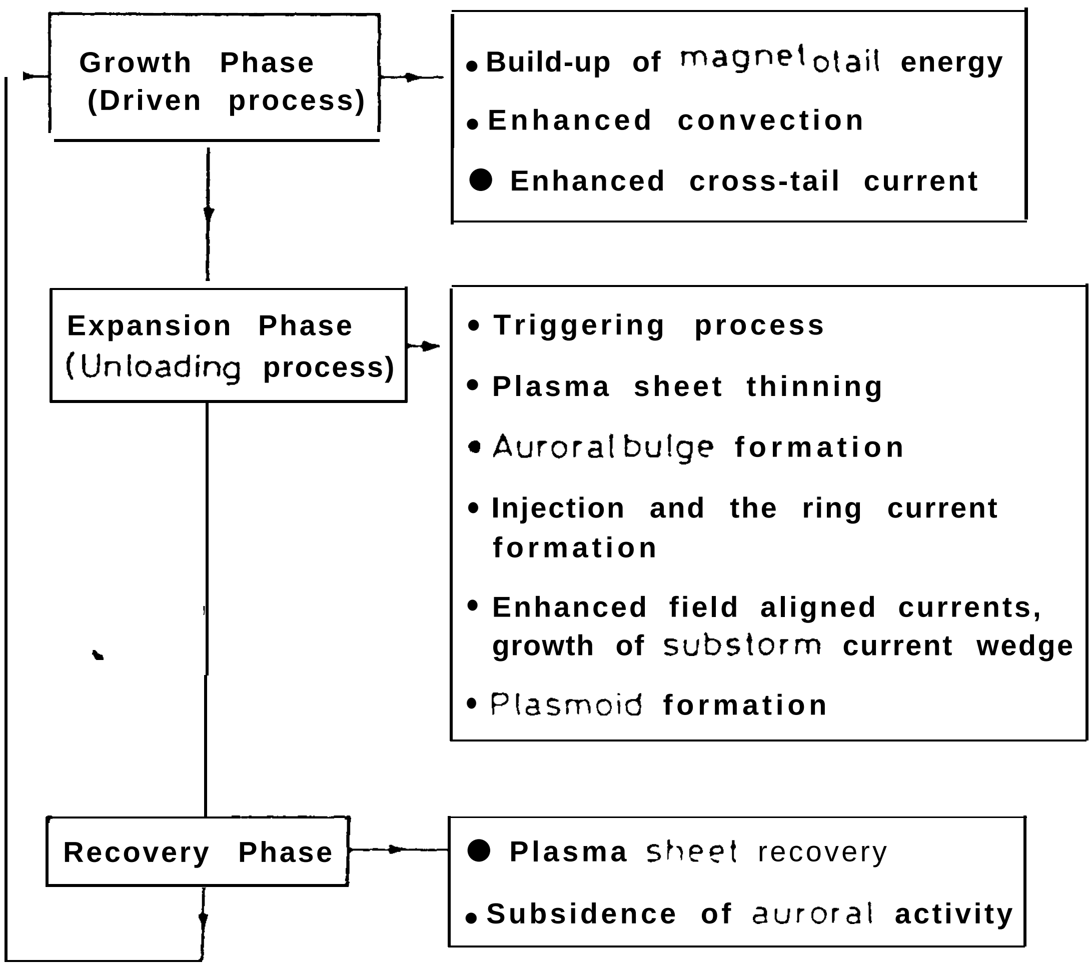
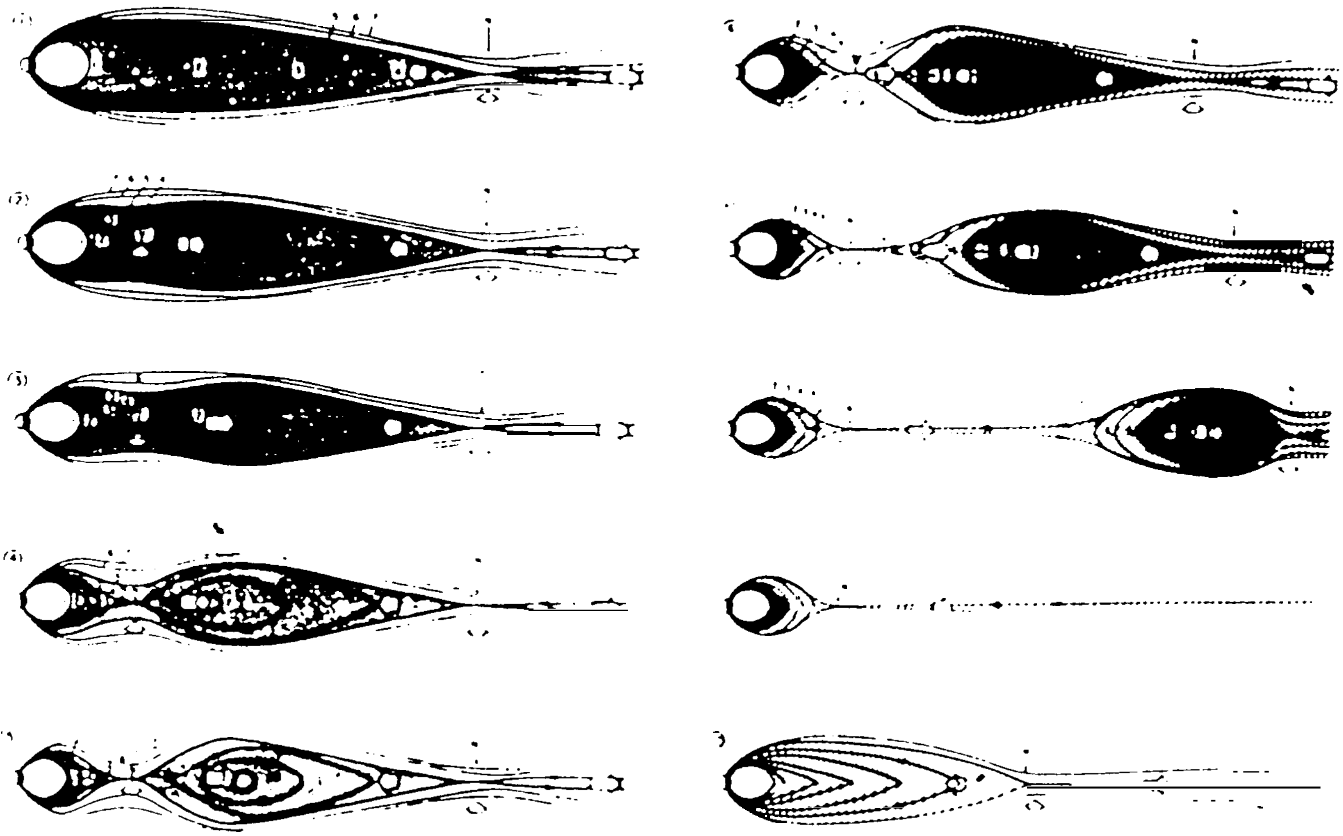


Fig. 10



Block diagram showing important events taking place during various phases of magnetospheric substorm.

Fig 11



12

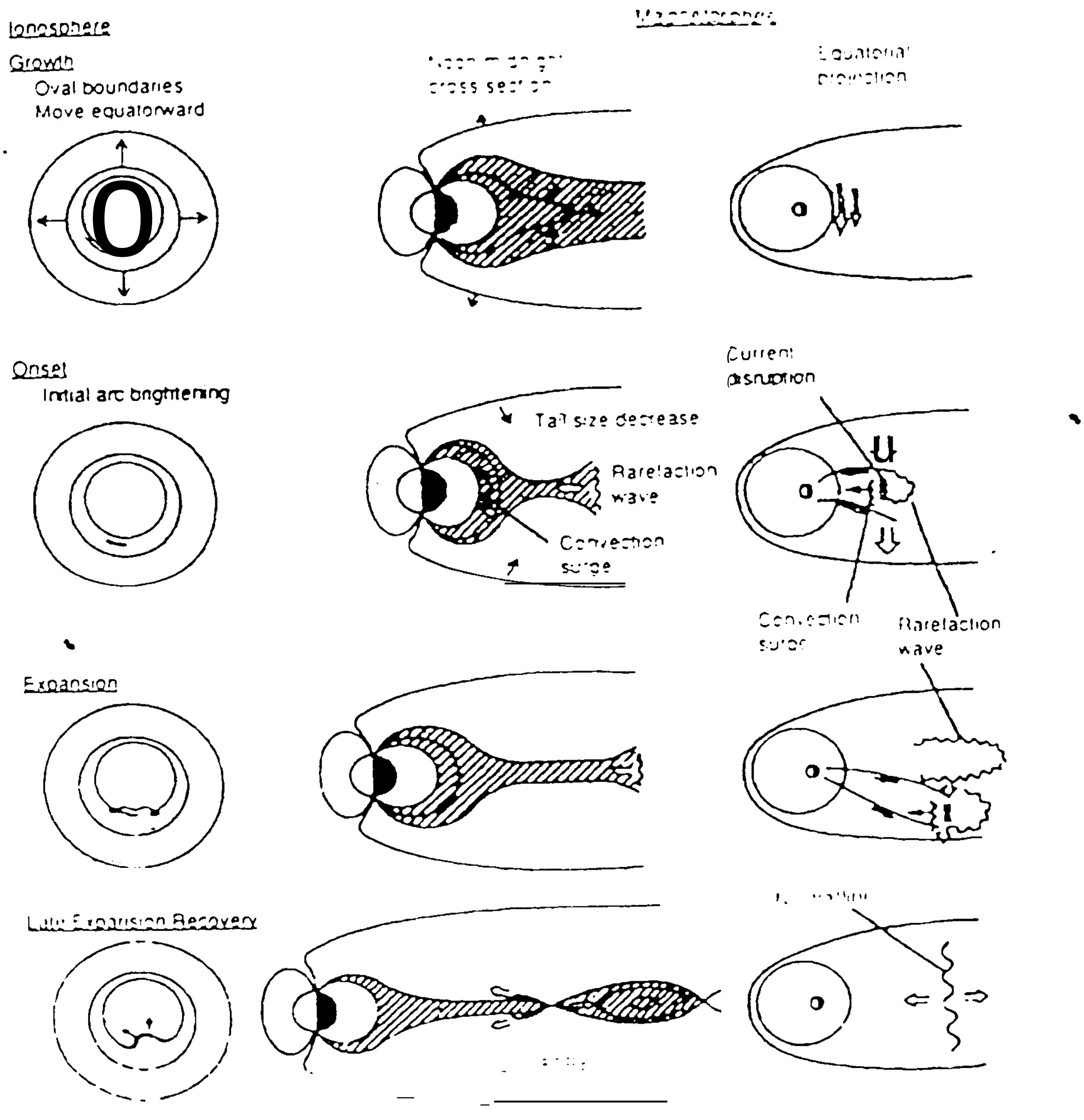

Ionosphere
Growth
Oval boundaries
Move equatorward
Onset
Initial arc brightening
Tail size decrease
Rarefaction wave
Convection surge
Current disruption
Convection surge
Rarefaction wave
Expansion
Late Expansion Recovery

Fig. 13

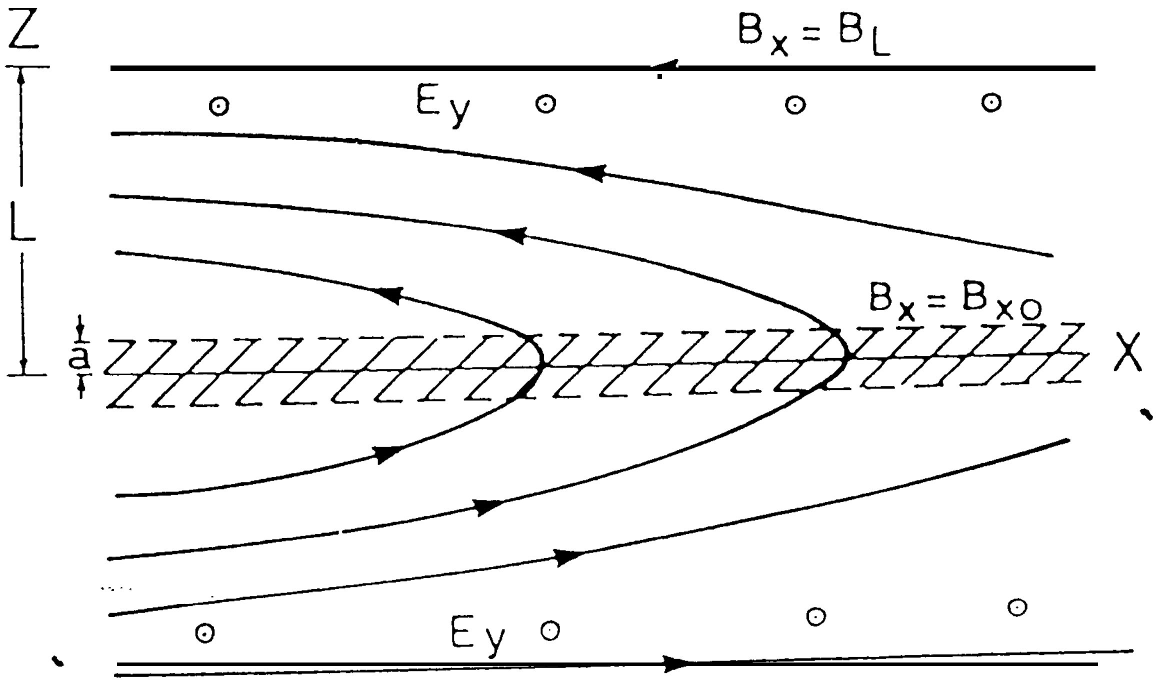


Fig. 14

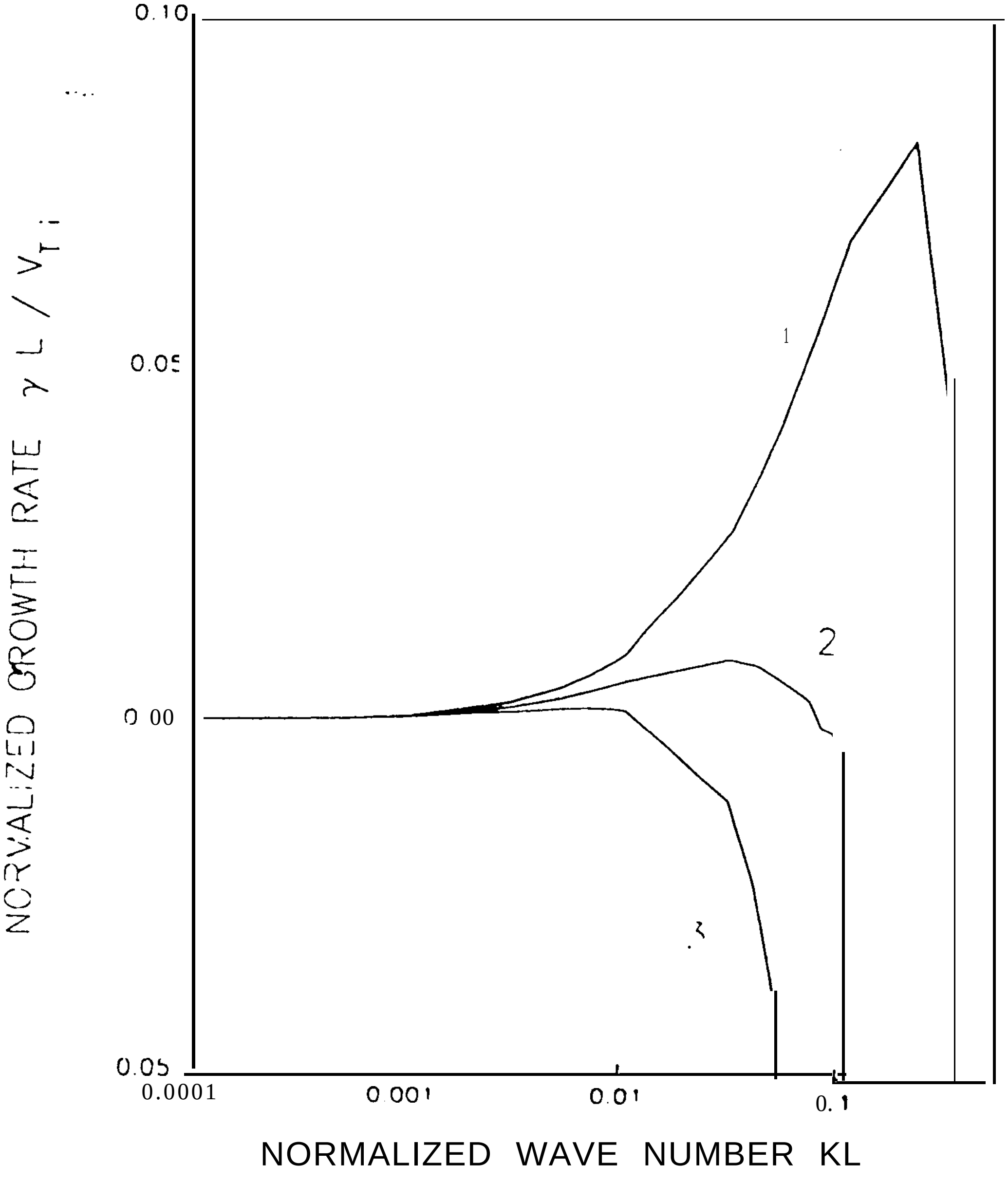

0.10
0.05
0 00
0.05
0.0001
0.001
0.01
0.1
1
2
3
NORMALIZED GROWTH RATE γ L / V_{Ti}
NORMALIZED WAVE NUMBER KL

fig. 15

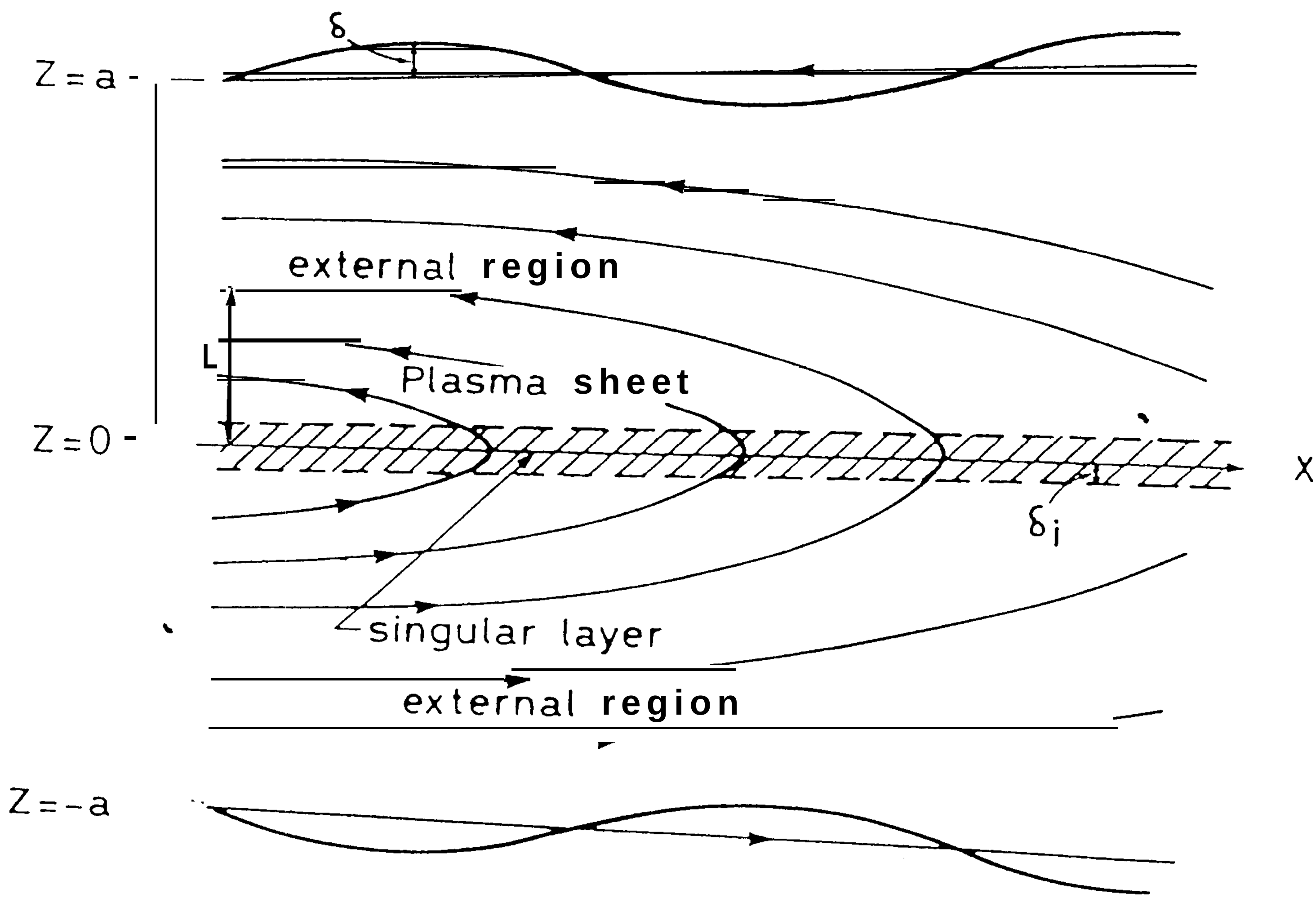

δ
Z = a
external region
L
Plasma sheet
Z = 0
X
δi
singular layer
external region
Z = -a

Fig. 16

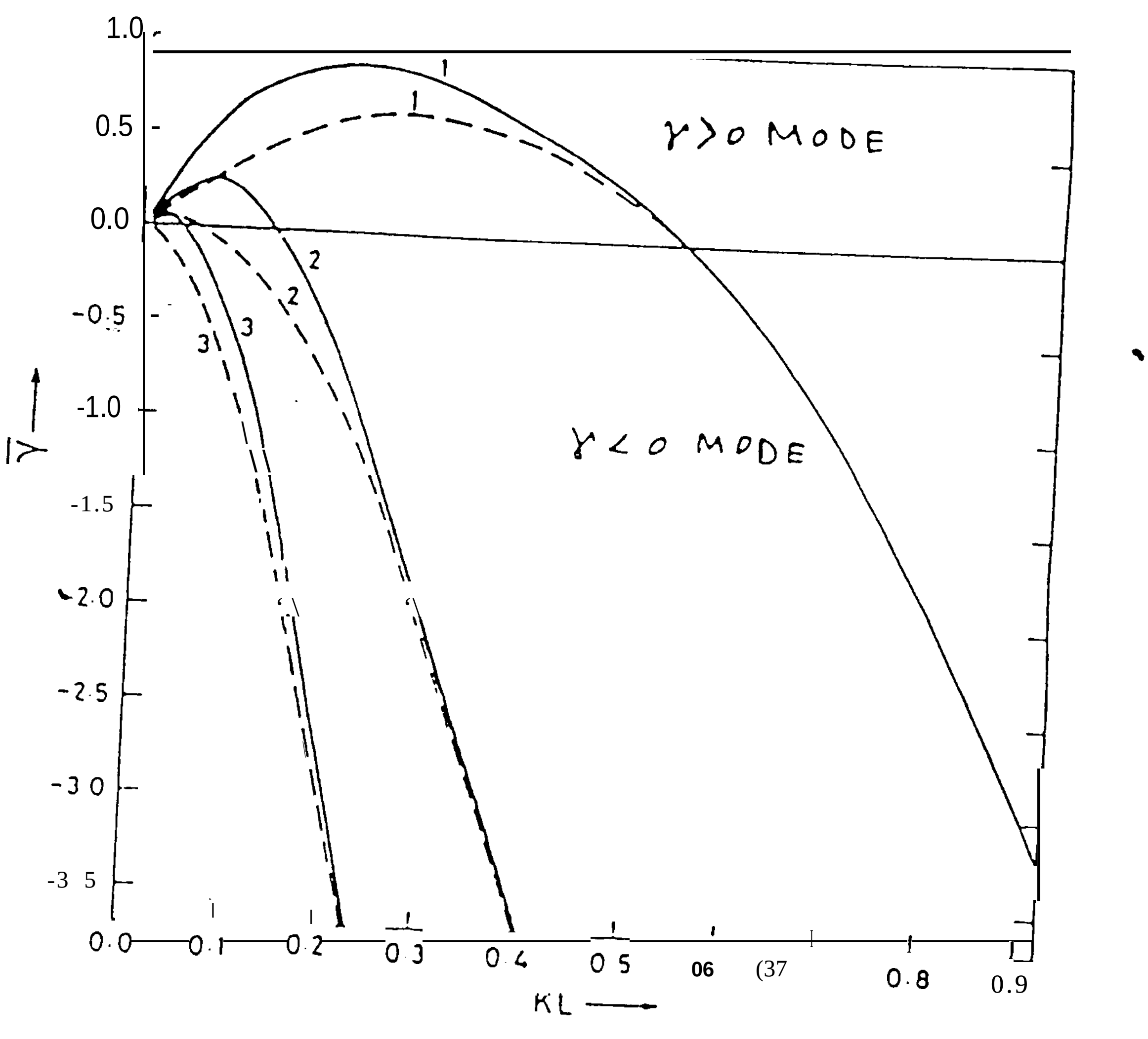

1.0
0.5
0.0
-0.5
-1.0
-1.5
-2.0
-2.5
-3 0
-3 5
0.0
0.1
0.2
0 3
0.4
0 5
06
(37
0.8
0.9
KL
$\bar{\gamma}$
1
1
2
2
3
3
$\gamma > 0$ MODE
$\gamma < 0$ MODE

Fig 17